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ELECTRONIC CIRCUITS AND SYSTEMS AND ELECTRONIC APPLICATIONS

COURSE 74

7-W

IMPORTANT NOTICE

Course 74 contains three large schematics. They are located directly below this instruction sheet. These schematics are: Figure 21 (page 32A) of Lesson 7425, and Figures 2-4 (page 46A) and 2-12 (page 58A) of Lesson 7445. You can take these schematics out of this volume and place them alongside the text material as you study those circuits.

After you have finished studying the material in this volume, you may wish to file the schematics with the lessons to which they refer. To make this easy, each schematic has the lesson name near the upper right-hand edge of the sheet and the lesson and page numbers in the lower left-hand corner.

ELECTRONIC CIRCUITS AND SYSTEMS AND ELECTRONIC APPLICATIONS

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LINEAR INTEGRATED CIRCUITS

7405

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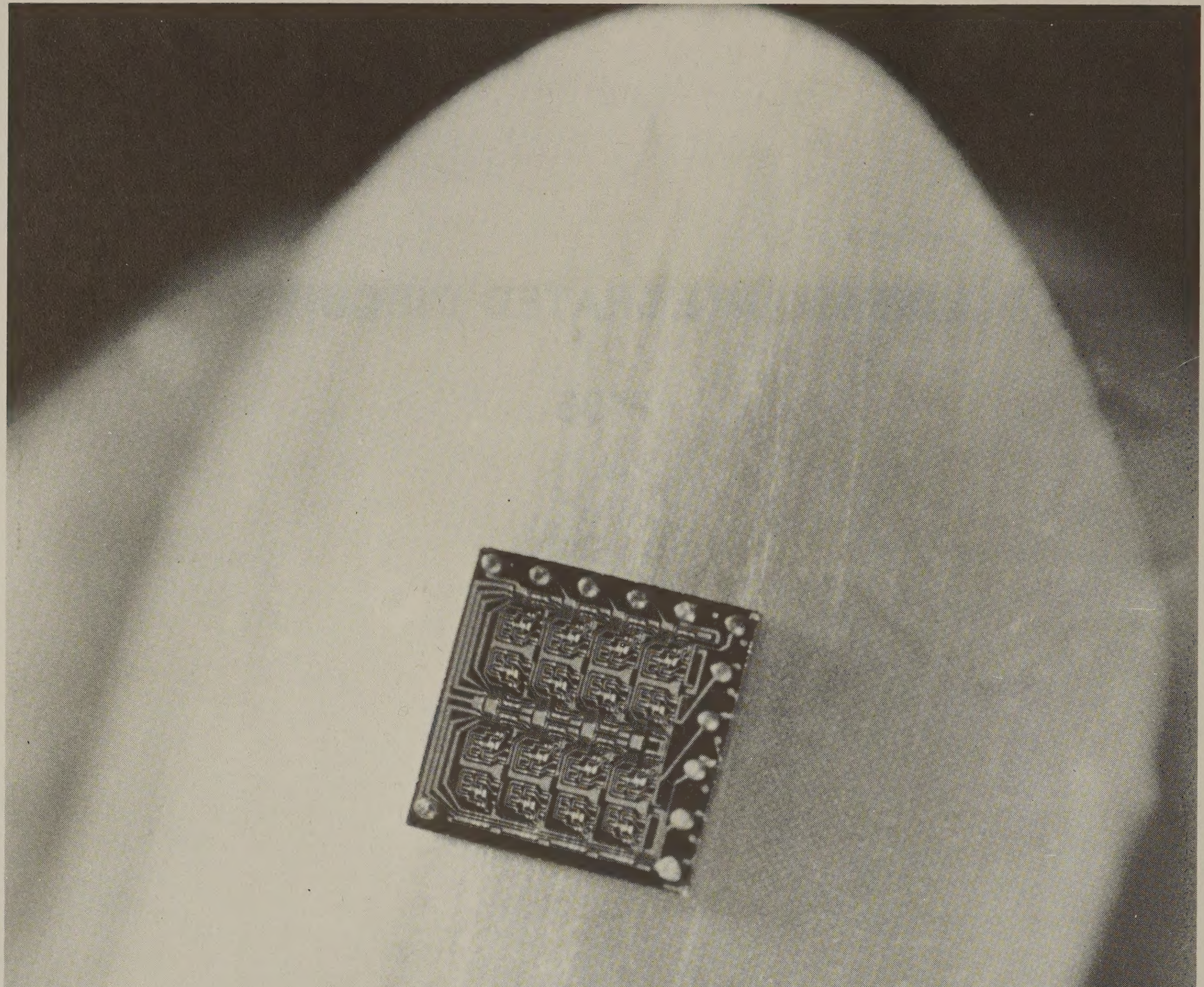

A 16-bit monolithic memory chip is shown on a man's fingernail. One chip has 16 circuits, with four auxiliary diodes. Each circuit has five transistors and four resistors.

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No student knows his subject:
the most he knows is where and
how to find out the things he
does not know.
—Woodrow Wilson

LINEAR INTEGRATED CIRCUITS

Integrated circuits have become quite important in electronic circuit design. Their earliest applications were in the computer industry, where they permitted miniaturization which is not possible with discrete components. IC's are now being used in increasing numbers in all types of electronic equipment.

The most obvious advantage of an integrated circuit is its small size compared to that of an equivalent circuit made up of discrete components. However, integrated circuits provide two additional advantages which account for much of their popularity. One is reliability, due to the long, trouble-free service inherent to a well-designed IC. The other is economy—although the initial cost of designing and fabricating an IC is high, mass production can bring the cost below that of a comparable discrete component circuit.

Integrated circuits are classed as digital or analog, according to their mode of operation. **DIGITAL CIRCUITS** are essentially "switching" circuits that use "on" or "off" states to represent some quantity or operation. In **ANALOG CIRCUITS,** the electrical signals vary in proportion to the quantities they represent. That is, the electrical signals are "analogous" to the physical quantities.

Analog circuits are also referred to as **LINEAR CIRCUITS.** A simple example of an analog or linear circuit is a phonograph amplifier, in which electrical signals vary in proportion to the sounds that were originally recorded. Oscillators, modulators and other circuits that produce or process analog information are all considered to be linear circuits.

In this lesson we will investigate the methods of producing linear circuits in integrated circuit form. We will consider the basic properties of linear integrated circuits and see how linear IC's are used in typical applications.

THE NATURE OF LINEAR INTEGRATED CIRCUITS

An integrated circuit is a combination of active elements (transistors and diodes) and passive elements (resistors and capacitors) fabricated on a semiconductor "chip." Most linear IC's are produced by the **MONOLITHIC PROCESS.** In this process, all active and passive elements are formed on or within the single piece of semiconductor material, usually silicon. The fabrication process itself is simply an extension of the process used to fabricate silicon bipolar junction transistors.

All active and passive elements are formed simultaneously by a diffusion process and are then interconnected to form the desired circuit by a metallization process. The monolithic process is economical because a large number of identical "chips" can be produced on a single wafer of semiconductor material. The chips are separated to form the individual circuits, which are then supplied in chip form or sealed in protective cases.

The monolithic process has certain desirable features in addition to economy. Because like elements are formed simultaneously, they have almost identical characteristics. Also, because these elements are formed very close to each other in a single piece of material, the thermal characteristics are almost perfectly matched.

A limitation of the monolithic process is the inability to form the large values of resistance and capacitance required in many linear circuit applications. There is no practical method of forming large values of inductance, or of producing transformers in integrated form. If these elements are required, external discrete components are connected to the terminals of the integrated circuit.

The need to avoid inductive components and to work with limited values of resistance and capacitance has led IC manufacturers to adopt design practices not generally used with conventional circuitry. In conventional circuit design, it is customary to minimize the number of passive and active (especially active) components because cost is determined largely by the number of parts used. In IC design, there is a greater tendency to use somewhat large combinations of transistors and diodes. In fact, a linear IC may contain 8 or 10 transistors connected in various ways to achieve the same result as would be obtained with a single transistor in a discrete circuit. This is economically feasible with IC chips because the method of fabrication allows several components to be "built" with the same ease as a single component. Additional transistors can be added to the chip for a cost of less than a penny for each extra transistor.

When push-pull and other forms of "matched" stages are used in discrete circuitry, it is generally at a penalty of increased cost. This is true because the transistors and other components must be sorted from stock to find matched pairs. Even then, matching is not always as good as desired. However, when transistors are formed on a single monolithic chip, all the base regions are formed in one set of operations, all emitter regions in another set of operations and all collector regions in another set of operations. The resultant transistors have very closely matched characteristics.

Although it is hard to achieve close tolerances on the absolute values of passive components, the ratios of these values can easily be held to 5% or less. Thus, integrated circuit technology lends itself readily to circuits whose characteristics depend on ratios rather than absolute values, particularly for symmetrical stages and networks.

BASIC LINEAR CIRCUIT ARRANGEMENTS

The design philosophies just considered have led to certain basic circuit arrangements that are encountered again and again in linear integrated circuits. Two of these circuits, the cascode amplifier and the differential amplifier, are manufactured as individual integrated circuits and, particularly the differential amplifier, are used as "building blocks" for more elaborate circuits.

Cascode Amplifiers

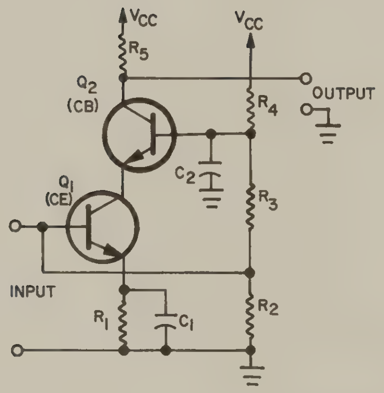


Figure 1

The **CASCODE AMPLIFIER**, consisting of a two-stage pair of direct-coupled common-emitter and common-base transistors, is a popular element in linear integrated circuitry. The cascode circuit has basically the same input and output characteristics as a common-emitter amplifier, but it is capable of providing higher gain and is inherently more stable. Because of these characteristics the circuit is ideally suited for high-frequency applications. This circuit is not encountered very often in discrete circuitry because of the large number of resistors and capacitors required to provide bias and prevent undesirable feedback. Figure 1 shows a discrete cascode stage. Resistors R_1, R_2, R_3 and R_4 form a bias network for Q_1 and Q_2. C_1 and C_2 provide ac signal ground paths from the Q_1 emitter and Q_2 base, respectively. Figure 2 shows the simplification achieved by fabricating the cascode stage on an IC chip. Bias on Q_1 and Q_2 is provided by the combination of R_1, R_4 and the diodes. The diodes also provide thermal stability because their thermal characteristics closely match the junction characteristics of the transistors. If the operating points of the transistors start to drift, the change in current through the diodes tends to negate this drift. The cascode configuration has become one of the "standards" of linear IC technology because of its simplicity and high stability.

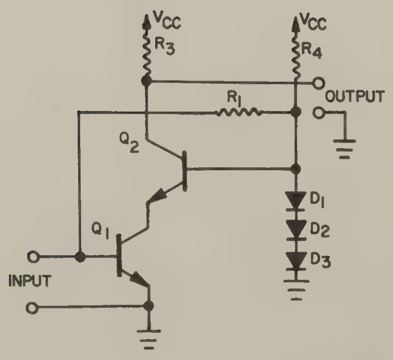


Figure 2

Commercial IC's using the cascode arrangement are usually a little more complex than the basic circuit of Figure 2. This circuit does not offer much flexibility—it simply provides an input and an output, with fixed operating characteristics. It also leaves a lot of wasted space on the chip. A more representative example of the IC cascode amplifier is shown in Figure 3.

In this circuit, Q_1 and Q_2 form the cascode common-emitter and common-base amplifier, biased through resistor R_8 and three series diodes. The

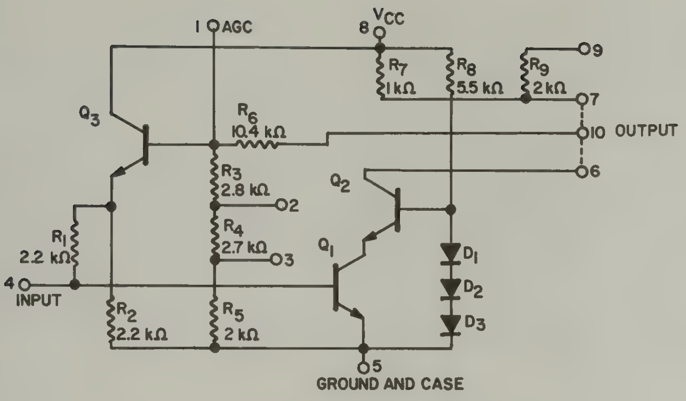


Figure 3

forward biased diodes have very low impedance to ac signals and they provide the common base connection for Q_2. Negative feedback is provided through Q_3 to stabilize the transistor operating points. This makes the circuit extremely stable, and also allows circuit gain adjustment by controlling the base voltage of Q_3. This is done with an external dc voltage at terminal 10. External connections to provide **AUTOMATIC GAIN CONTROL (AGC)** are made through terminal 1. This permits an external feedback signal or the signal from some control circuit to be used to regulate the gain of the amplifier. The other terminals (aside from the input, output, supply and ground points) are provided so that the user may make external connections and modify the operation of the circuit. For example, pin 2 or pin 3 can be shorted to pin 5 to change the gain of the circuit. Providing extra terminals to change the circuit configuration permits a given IC type to be used in a variety of circuit arrangements. This is a common feature of most IC's, which lowers their cost by allowing manufacturers to provide large quantities of fewer types to be used in many different applications. This greatly reduces the high tooling costs that are required prior to producing each type of IC.

In keeping with the IC design philosophy stated earlier, the circuit is arranged so that the voltage gains obtained depend on resistance ratios rather than absolute resistance values. The input characteristics are essentially those of a single stage common-emitter transistor amplifier. The output characteristics are those of a single stage common-base amplifier.

Differential Amplifiers

The "workhorse" of linear integrated circuitry is the **DIFFERENTIAL AMPLIFIER.** As shown by the simplified diagram of Figure 4A, the basic differential amplifier consists of two transistors and their collector load resistors which form two legs of a bridge. Each transistor serves as a

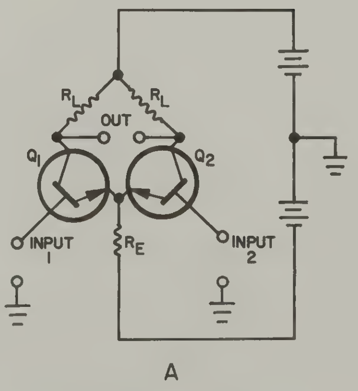


Figure 4

common-emitter amplifier, with the two sharing a single emitter resistor. Input terminals are provided for the base of each transistor. Output terminals are provided at the collectors of the transistors.

Emitter resistor R_E carries the collector currents of both transistors. If its resistance value is sufficiently large, R_E serves as a constant current source. That is, it tends to maintain a constant current between the negative supply terminal and the emitters of Q_1 and Q_2. If the collector current of one transistor increases, the collector current of the other will decrease by the same amount to maintain the constant current through R_E.

Assuming that the transistors and the collector load resistors are perfectly matched, with no input signals on the bases, there will be equal collector currents in the two legs of the bridge. If the output is taken between the two collector terminals, there is zero output voltage. If signals of equal amplitude and polarity are applied to both sets of input terminals, the collector currents and collector voltages remain equal, and the output remains zero. Thus, for equal inputs to the differential amplifier, the differential output voltage (collector-to-collector) is zero. This type of operation is referred to as **COMMON MODE OPERATION**.

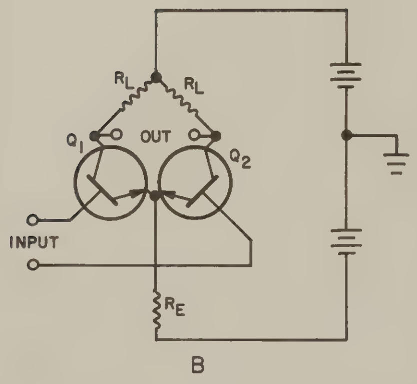


Figure 4

If, however, a signal is applied BETWEEN the two input terminals as shown in Figure 4B, one base is driven positive and the other is driven negative. If the Q_1 base is driven positive and the Q_2 base negative, Q_1 collector current increases and Q_2 collector current decreases. As a result, Q_1 collector voltage decreases and Q_2 collector voltage increases. This produces a voltage difference between the output terminals, with the one at Q_2 more positive.

If the Q_1 base is driven negative and the Q_2 base positive, opposite conditions occur, and the resultant output is more positive at the Q_1 collector end. Thus, an output voltage appears only when there is a difference of potential between the two inputs. This mode of operation is referred to as **DIFFERENTIAL MODE OPERATION**. The ratio of the differential output voltage to the differential input voltage is referred to as the **DIFFERENTIAL VOLTAGE GAIN (A_d)** of the amplifier.

The differential amplifier is a versatile circuit. In the operation just described, the amplifier provides a differential output in response to a differential input. This operation can be modified by connecting one of the input terminals to a reference voltage (or to ground) and applying a signal to the other input. The circuit then serves as a **COMPARATOR**, generating an output voltage that is proportional to the difference between the input signal and the reference potential.

The IC differential amplifier chip can also be used as a simple inverting or noninverting amplifier by applying a signal between one of its input terminals and ground, and taking the output between the appropriate output terminal and ground. As an example, with an input applied between the Q_1 base and ground, and the output taken between the Q_1 collector and ground, the circuit provides inverter operation. With the input at the Q_1 base and the output at the Q_2 collector, the circuit functions as a noninverting amplifier.

The bulk of the IC chip, called the substrate, is the portion that holds the component regions. The substrate is usually connected to circuit ground.

Common mode operation of a differential amplifier provides an important advantage in many applications. Undesired signals such as noise and other forms of interference tend to be injected with equal amplitude and polarity into both inputs. Because equal common mode input signals produce zero output, the differential amplifier is quite effective in rejecting undesired signals.

In practice, slight variations in component values prevent complete rejection of common mode signals. The ratio of common mode output voltage to common mode input voltage is called the **COMMON MODE VOLTAGE GAIN (A_c)**. This gain is usually far less than 1. The ratio of common mode voltage gain to differential mode voltage gain is the **COMMON MODE REJECTION RATIO (CMRR)** of the amplifier, expressed in decibels. Typical CMRR ratings are -80 to -120 dB. That is, undesired common mode signal outputs are 80 to 120 dB below the desired output.

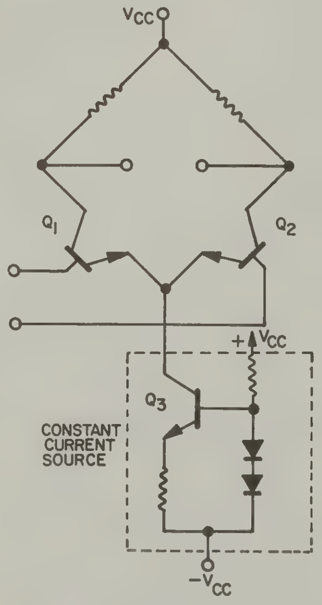


Figure 5

A more practical version of a differential amplifier is shown in Figure 5. In this circuit, emitter resistor R_E has been replaced by transistor Q_3 and its bias resistors. Transistor Q_3 serves as a constant current source. The constant voltage drop across the diodes holds the Q_3 base-emitter junction at a constant potential. This keeps Q_3 collector current constant. Because a constant current source has a high impedance, the Q_1 and Q_2 emitters are therefore connected to a high impedance source. However, transistor Q_3 does not limit total Q_1 and Q_2 emitter current as would a high value resistor in this position.

Mismatches between the components in the two "halves" of a differential amplifier can cause slight output signal distortions when the IC is used as a differential mode amplifier. These mismatches also prevent the circuit from completely rejecting unwanted common mode input signals, and they introduce errors when the circuit is used as a voltage comparator. This mismatch causes a voltage to be produced at the output even when no input signal is applied, and this output is called the **OUTPUT OFFSET VOLTAGE**.

Two types of quantities are specified for differential amplifiers to compensate for the output offset. The **INPUT OFFSET VOLTAGE** is the difference in base-emitter voltages (input voltages) required to produce equal collector voltages for the two transistors. This value is typically 1 or 2 millivolts. The **INPUT OFFSET CURRENT** represents the difference in the base currents (input bias currents) required to produce equal collector voltages. Input offset current is an indication of the imbalance between the current gains (β) of the two transistors. It is typically less than 0.5 μA.

The required input offset voltages and currents are usually specified for an operating temperature of 25°C. The change in required input offset voltage or current with temperature is designated as **OFFSET DRIFT,** usually plotted as a curve between −50°C and +125°C. Typical voltage offset drift is about 2 mV and typical offset current drift is about 1 μA within this range.

Another important current rating is the **INPUT BIAS CURRENT.** This is the average current drawn by the base-emitter circuits of the differential amplifier, with no input signal applied. It should be kept as low as possible to minimize offset. Input bias current varies considerably from one circuit to another, depending upon the type of input circuitry used. It can range as high as 100 μA or greater in some amplifiers, to less than 1 μA in others. It is determined by the input impedance of the amplifier. The higher the input impedance is, the smaller the input bias current will be.

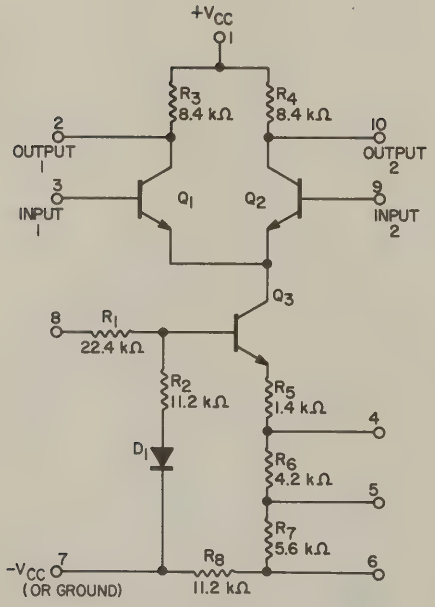


Figure 6

A typical IC differential amplifier is shown in Figure 6. Q_1 and Q_2 are the differential amplifier, with Q_3 as the constant current source, biased through R_1, R_2 and D_1. The gain of the stage can be changed by shorting out sections of the Q_3 emitter-resistor divider (R_5R_8). The differential signal inputs are pins 3 and 9, and the outputs are taken at pins 2 and 10. The power supply is connected between pins 1 ($+V_{CC}$) and 7 ($-V_{CC}$). The use of separate positive and negative power supplies provides convenience in obtaining proper dc signal and biasing levels. This also eliminates the need for extra active device stages that would normally be required to obtain the correct dc signal levels. A simple V_{CC} supply would be used, however.

Pin 8 provides a biasing input point to the base of Q_3. Internally developed AGC can be implemented by connecting an external resistor between pin 8 and pin 2 or 10, or an external control signal can be applied to pin 8 to regulate the stage gain.

DIFFERENTIAL/CASCODE AMPLIFIER APPLICATIONS

A number of differential and cascode amplifier circuits are manufactured in IC form. These circuits are usually designed with broad operating characteristics and a variety of terminal connection options so that the user can "tailor" the characteristics to his application.

The CA3000 integrated circuit dc amplifier of Figure 7 is an example of a versatile differential amplifier. It can be used as an amplifier, a modulator, an oscillator or in other services by selection of the appropriate external connections and circuits.

This IC contains a single stage differential amplifier composed of Q_2 and Q_4, with Q_3 serving as a constant current source. A differential output can be taken between pins 8 and 10, or a single-ended output can be taken between either of these pins and ground. The 50Ω emitter resistors R_4 and R_5 in the differential stage provide degeneration that reduces the maximum gain but provides more uniform gain over the operating frequency range.

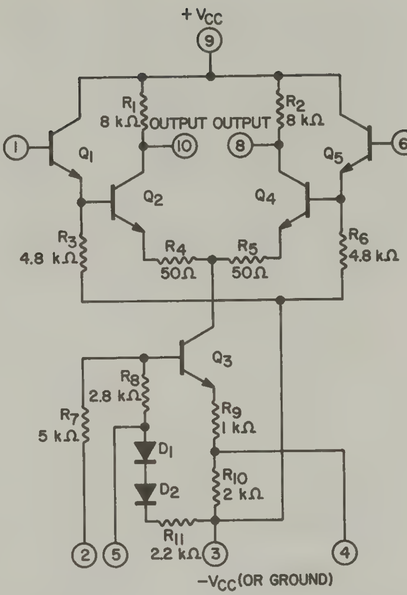


Figure 7

The inputs are applied at pins 1 and 6 to emitter-follower stages Q_1 and Q_5, which exhibit a relatively high input impedance characteristic of the emitter-follower (common-collector) configuration. These stages provide input impedances of approximately 100 kΩ. Typical input bias current is 23 μA, with an input offset current of 1.2 μA and input offset voltage of 1.4 mV. Typical voltage gain is over 30 from dc to 1 MHz. An automatic gain control voltage can be applied at pin 2 to control the conduction of Q_3 to regulate the gain of the amplifier.

The basic CA3000 amplifier configuration is shown in Figure 8. Here we have used the logic symbol for an amplifier to represent the IC amplifier. This symbol is a triangle, with the input represented by the straight edge and the output by the pointed end. The various terminals or pins are designated at convenient points on the symbol.

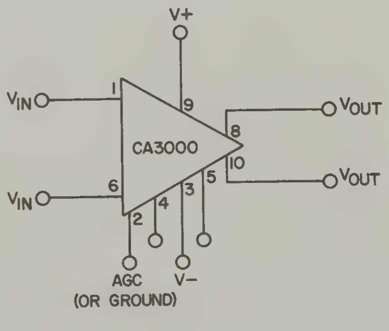


Figure 8

Typical bias supply voltages are +6 volts ($+V_{CC}$) and −6 volts ($-V_{CC}$). These voltages can be obtained from a single supply with a voltage divider, but separate supplies are preferred. The user has an option of altering the internal bias arrangement in the base-emitter circuit of Q_3 by shorting various combinations of pins 3, 4 and 5. This gives him a method of setting the circuit gain.

Figure 9 shows the voltage gain of the CA3000 with an input signal applied to pin 1 and an output taken from pin 10. The amplifier output signal for different values of AGC voltage is shown in Figure 10. The output voltage gain curve is obtained for an AGC input range of 0 to −6 volts at pin 2, with a 1 kHz signal applied to pin 1 and the output taken from pin 10. Curves such

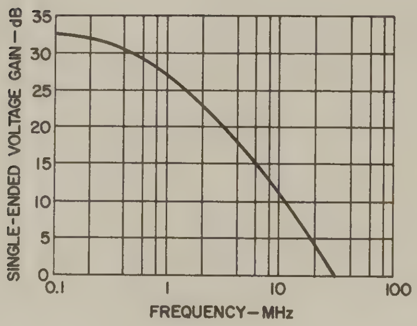


Figure 9

as these are provided in the manufacturer's specification sheets, and serve as guides for the user in selecting IC's for various applications.

The CA3000 can be operated as an oscillator by adding a crystal and only two external resistors, as shown in Figure 11. The crystal connects from output pin 8 to input pin 1. Pin 1 is connected to ground through a 1 kΩ load resistor. The other input, pin 6, is also grounded through a 1 kΩ load resistor. The output is taken from pin 10, the output collector not connected to the crystal. The oscillation waveform is shown in the diagram. The frequency is determined by the characteristics of the crystal, and the amplitude is determined by the gain selected for the stage.

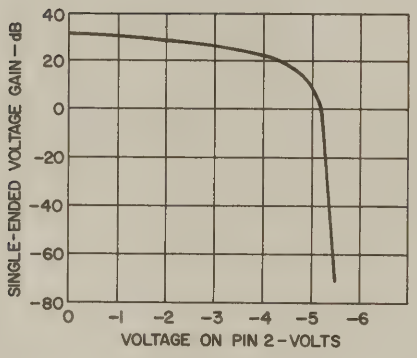


Figure 10

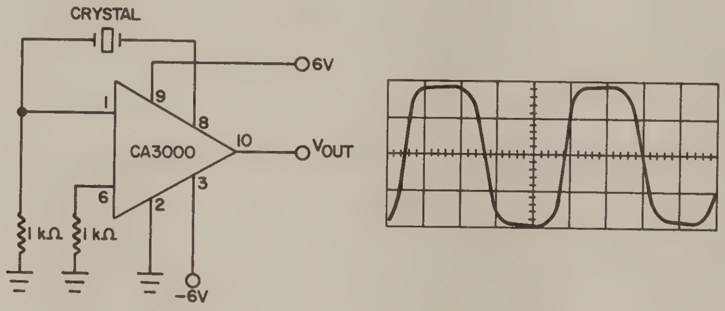


Figure 11

Figure 12 shows the circuit connected to produce modulation of the oscillator signal. A low-frequency modulating signal is applied to pin 2, the AGC input. This signal causes the stage gain to vary, thereby varying the amplitude of the oscillator signal in step with the modulating signal. The output is obtained through a high-pass filter at pin 10.

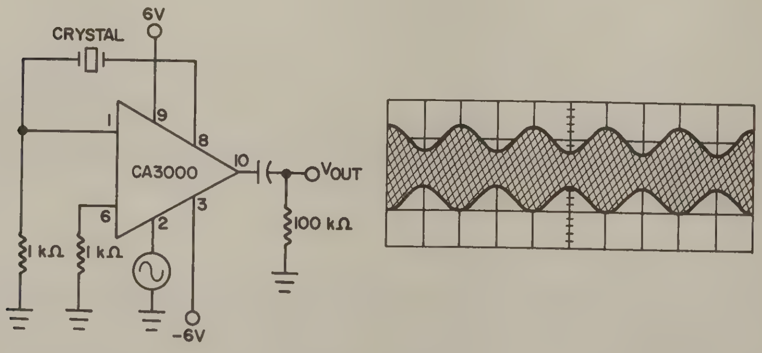


Figure 12

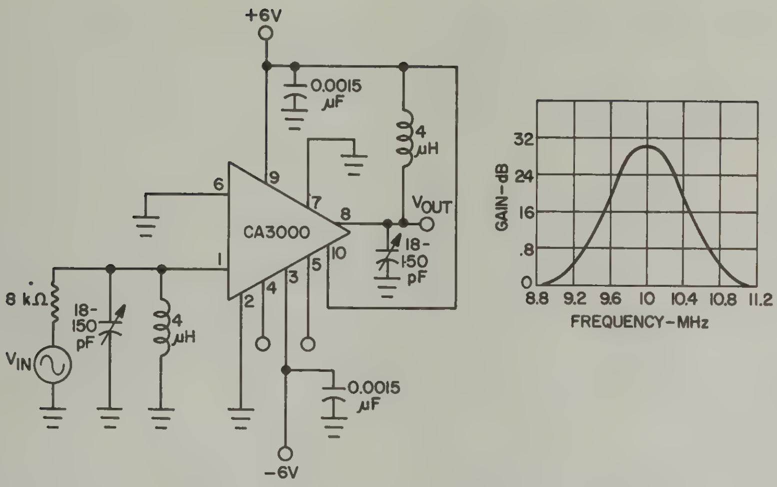


Figure 13

The CA3000 is capable of providing uniform gain over a range of frequencies from dc into the MHz region. However, it can be converted to a narrow-band amplifier by simply adding tuned circuits, as shown in Figure 13. The resulting frequency-gain curve shows the narrow-band response when these circuits are tuned to 10 MHz.

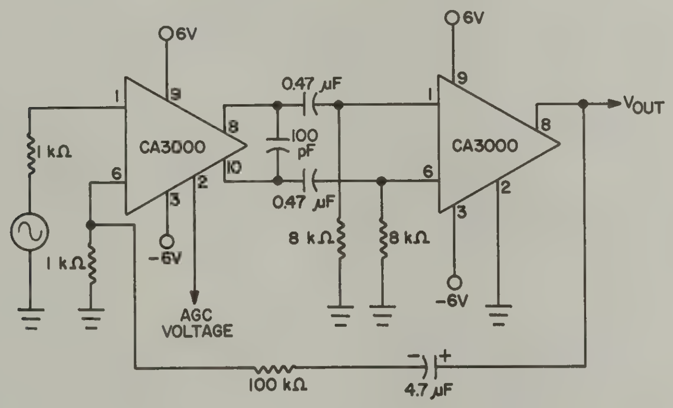


Figure 14

For greater gain, individual IC amplifiers can be cascaded in the same manner as discrete amplifiers. Figure 14 shows a two-stage cascade of CA3000 IC's. In this circuit the differential output of the first stage is applied as a differential input to the second stage through an RC coupling network. The basic cascade arrangement provides an overall voltage gain of over 1000 in a band of about 20 Hz to over 125 kHz, as shown in Figure 15. The bandwidth can be extended, at a sacrifice in gain, by using a negative

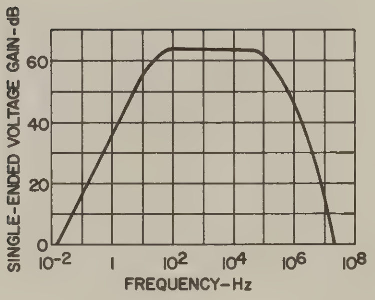


Figure 15

feedback network from the output of the second stage to one of the inputs of the first stage. This reduces the overall voltage gain to about 100, but extends the lower and upper frequency limits to about 1 Hz and 2 MHz, respectively. AGC can be applied to the first stage as indicated.

Another example of a general purpose IC is the MC1550, shown schematically in Figure 16. This circuit is designed primarily as a high-frequency **CASCODE AMPLIFIER** for i-f or r-f amplifier service. Pin 9 is the positive power supply terminal, with pins 2, 3 and 7 connected to the ground side of the supply. Pin 7 is connected to the substrate of the chip, and also to the metal case, to provide shielding and improve circuit stability.

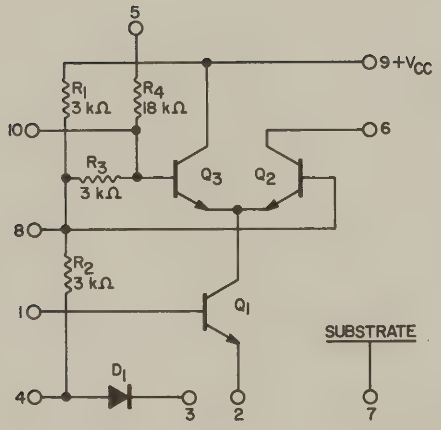


Figure 16

Q_1 and Q_2 form a cascode amplifier, biased by resistors R_1, R_2 and R_3 and by diode D_1. The diode presents a low impedance to high-frequency signals and effectively couples pin 4 to signal ground (pin 3). The ground side of the input does not go directly to pin 3 because if the input source has a low impedance, the high side of the input at pin 1 would cause the forward bias of Q_1 to be decreased through the low source impedance. The collector load for Q_2 is connected between pins 6 and 9. Therefore, the input signal is applied between pins 1 and 4, and the output is taken between pins 6 and 9. Pins 8, 9 and 10 are normally decoupled to ground for cascode operation. Transistor Q_3 is an emitter-follower AGC transistor, receiving its external control signal through R_4 from pin 5. With Q_3 biased "full-off," the amplifier has its greatest gain. The AGC signal at the Q_3 base varies the conduction of Q_1 in its emitter path, changing the amount of signal coupled to Q_2.

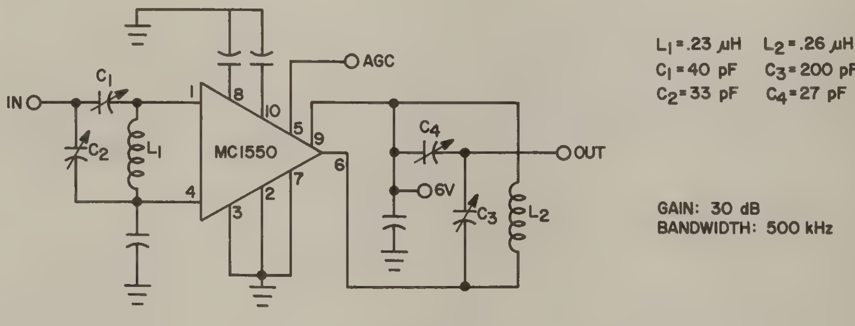


Figure 17

The external circuitry for using the MC1550 as a tuned high-frequency amplifier is shown in Figure 17. The inductance and capacitance values shown are for a center frequency of 60 MHz. A gain of 30 dB over a bandwidth of approximately 500 kHz is achieved.

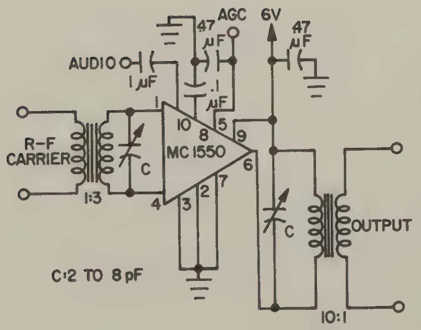


Figure 18

The MC1550 is connected as an amplitude modulator in Figure 18. The AGC stage is used as a modulator for r-f signals being amplified by the cascode pair. The external r-f signal to be modulated is coupled through a tuned circuit to Q_1 through pins 1 and 4. A 3.5 volt dc bias is applied to pin 5, and the modulating signal is applied directly to the base of Q_3 via pin 10. Therefore, the modulating signal "rides" on a 3.5 volt dc level. The purpose of this is shown in Figure 19. The relative forward transfer characteristic (voltage gain) for the cascode amplifier is shown as a function of the automatic gain control (AGC) voltage. The variation is linear from point A (2.75 volts) to point C (4.25 volts). By biasing between these two points (at point B), a maximum modulating signal variation of ±0.75 volt can be applied without distortion.

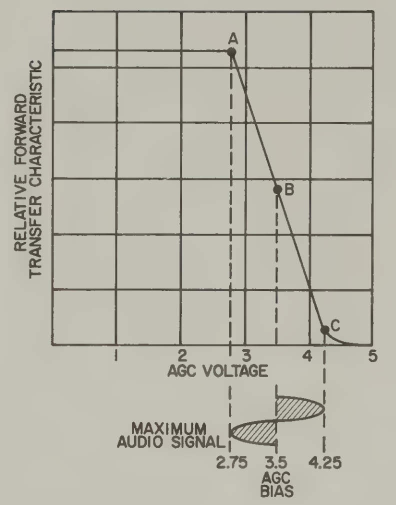


Figure 19

The MC1550 may be used to illustrate the versatility designed into general purpose linear IC's. Although it is designed primarily for cascode operation, the circuitry is arranged and terminals are provided to permit operation as a differential amplifier as well. For differential operation, Q_2 and Q_3 serve as the differential pair and Q_1 is the constant current source. Pins 8 and 10 are used as the input terminals, and pins 9 and 6 serve as the differential output terminals. With pins 1 and 4 connected together, diode D_1 provides the bias for Q_1. Figure 20 shows the MC1550 connected in the differential amplifier mode as a 10.7 MHz i-f amplifier for use in an FM radio receiver.

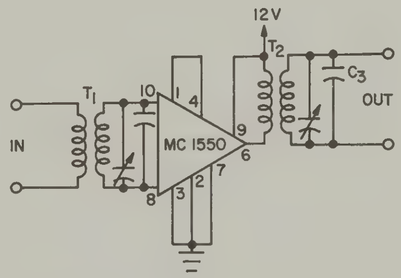


Figure 20

OPERATIONAL AMPLIFIERS

The mainstay of linear integrated circuitry is the **OPERATIONAL AMPLIFIER**, a circuit that can be inserted into almost any type of equipment to perform some "operation" electronically. The term operational amplifier stems from the original design of this type of circuit to perform mathematical operations such as addition, subtraction, integration and differentiation. However, "op amps" are now used as general purpose amplifiers in a variety of applications such as signal sensing, waveshaping and process control, to name a few.

An operational amplifier is basically a high gain, direct-coupled amplifier. In most applications, negative feedback is used to control the operation of the amplifier. As a general rule, if the gain of the amplifier is high enough, the characteristics of the circuit depend entirely on the arrangement of the external feedback components. This is what makes the op amp such a versatile device. The user can make it perform just about any operation that he wants by his choice of external components.

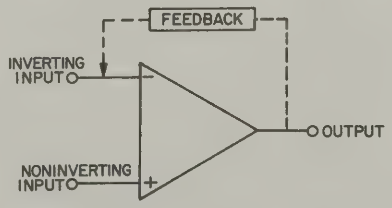
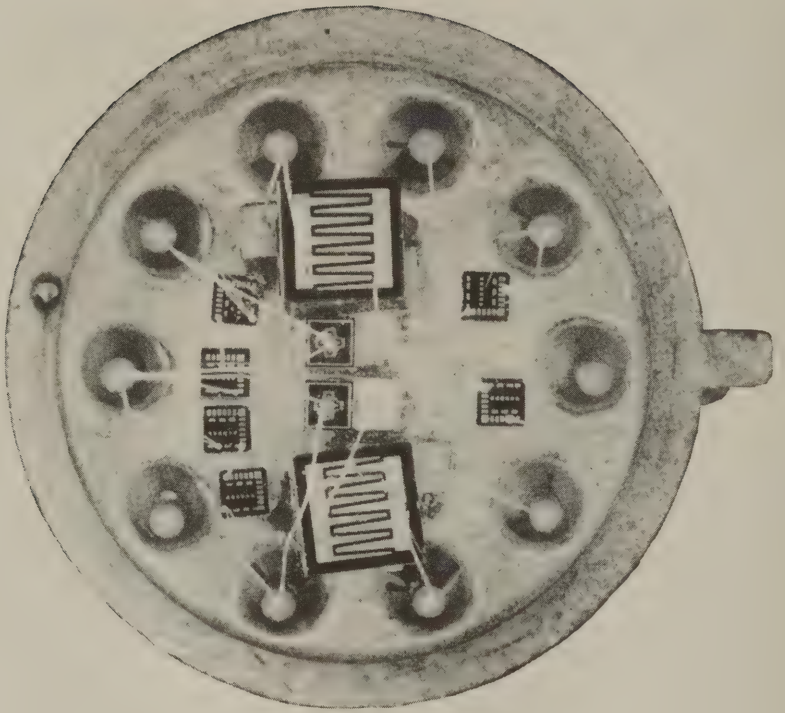


Figure 21

An operational amplifier is represented by the functional block symbol of Figure 21. The input stage of the amplifier is a differential amplifier operated in the differential mode. The differential inputs are designated by the (−) and (+) symbols. A second stage differential amplifier is normally used to obtain high gain, and this stage is directly coupled to the first stage. A single-ended



Many integrated circuits can be placed in a single package to form a complete multistage amplifier.
Courtesy Integrated Circuit Engineering Corp.

amplifier is then used as a third stage. This amplifier is directly coupled to one side of the second stage differential amplifier and therefore provides a single output. The (−) input is the inverting input. A signal applied to this input will produce an inverted (180° out-of-phase) signal at the output. The (+) input is the noninverting input. A signal applied to this input will produce an in-phase signal at the output. When negative feedback is used, it is applied from the output to the inverting input, as shown by the dashed lines in Figure 21.

An "ideal" operational amplifier would exhibit the following characteristics:

Infinite gain from dc to an infinite frequency.

Infinite input impedance; so that it draws zero current from the signal source.

Zero output impedance; so that it can supply any value of current demanded by the load.

Zero offset voltage and current.

Infinite common mode rejection ratio.

The following Practice Exercise questions cover the subjects which you have just studied. They are:

THE NATURE OF LINEAR INTEGRATED CIRCUITS

BASIC LINEAR CIRCUIT ARRANGEMENTS

CASCODE AMPLIFIERS

DIFFERENTIAL AMPLIFIERS

DIFFERENTIAL/CASCODE AMPLIFIER APPLICATIONS

1. How do analog (linear) and digital circuits differ as far as electrical operation is concerned?

2. List three desirable features of the monolithic process of producing integrated circuits.

3. Inductors and large value resistors and capacitors are easily produced by the monolithic process. True or False?

4. Why is it common practice to achieve some desired result by using combinations of active components in a monolithic IC?

5. In linear integrated circuits, balanced circuits such as push-pull amplifiers are easy to produce because of the closely matched characteristics of the components. True or False?

6. In linear IC design, the most common method of producing passive components is to produce them on the basis of (a) absolute values, (b) ratios of values.

7. The cascode amplifier has gained popularity in linear IC design because of its simplicity and inherent stability. True or False?

8. What is the purpose of the AGC input in the cascode circuit of Figure 3?

9. With equal input signals at the two sets of input terminals of the differential amplifier of Figure 4A, the collector-to-collector output is (a) maximum, (b) zero.

10. In common mode operation, two equal input signals are applied to the two inputs of a differential amplifier. True or False?

11. What is the function of R_E in Figure 4?

12. In Figure 4A, if the base of Q_2 is driven positive with respect to the base of Q_1, the collector current of Q_1 will (a) increase, (b) decrease, (c) remain the same.

13. The ratio of common mode voltage gain to differential mode voltage gain in a differential amplifier is called the ________ ________ ________ ratio.

14. What term is used to indicate the degree of mismatch between the two "halves" of a differential amplifier?

15. The average current drawn by the base-emitter circuits of a differential amplifier with no input signal applied is called input offset current. True or False?

16. To keep the input bias current low, the input impedance of a differential amplifier must be (a) high, (b) low.

17. AGC is applied at pin ____ in the circuit of Figure 6.

Zero response time; so that output voltage changes occur simultaneously with input voltage changes.

Although it is impossible to construct a perfect amplifier, these ideal characteristics are useful in analyzing the basic operating principles of op amps, and in observing the effects of standard feedback arrangements.

Standard Configurations

The four standard configurations of operation amplifiers are illustrated in Figure 22. Figure 22A shows the **OPEN-LOOP CONFIGURATION.** The op amp simply functions as a high-gain amplifier without feedback. The amount of amplification depends entirely on the **OPEN-LOOP GAIN (A_O)** of the amplifier itself. Input signal E_{IN} is applied through R_1 to the inverting input. The noninverting input is grounded. A single output is taken with respect to ground.

If E_{IN} is zero, the output of Figure 22A is also zero. Any input that is just slightly greater than zero causes E_O to go to the saturation level due to the very high gain of the amplifier. Thus, an operational amplifier operated open loop functions as a switch, with the output switching between zero and saturation.

Figure 22B shows the basic amplifier with a feedback loop directly from the output to the inverting (−) input. The input signal is applied between the noninverting (+) input and ground. In the ideal amplifier, there is no current into the inverting input because of the infinite input impedance, so the difference of potential between the (+) and (−) inputs is zero. With E_O applied to the (−) input, and no difference of potential between the (−) and (+) inputs, the voltages E_O and E_{IN} are equal. Thus, the **CLOSED-LOOP GAIN (A_C)** of the circuit is 1, or unity.

The circuit of Figure 22B is called a **VOLTAGE FOLLOWER** because the output voltage "follows" the input voltage. Although it does not provide a voltage gain, it is useful as a buffer or isolating stage. Also, with its extremely high input impedance and almost zero output impedance, the voltage follower permits an extremely low current source to drive a load which requires substantially more current.

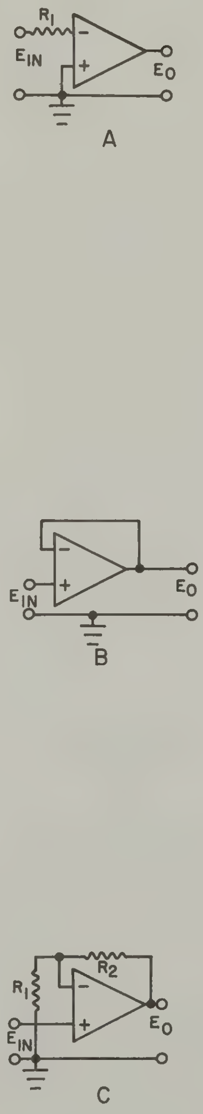


Figure 22

The circuits of Figures 22C and 22D are the most common operational amplifier configurations. Figure 22C shows the **NONINVERTING CONFIGURATION.** Feedback is supplied to the inverting input by voltage divider R_1R_2. This divider is between E_O and ground, so the output voltage divides between R_1 and R_2 in proportion to their resistance values.

Again assuming ideal conditions, there is no current into the (−) input so the (−) and (+) terminals are at the same potential. This places E_{IN} across R_1. The ratio of E_O to E_{IN} is therefore equal to the ratio of $(R_1 + R_2)$ to R_1. The closed-loop gain of the circuit is:

$$A_C = \frac{R_1 + R_2}{R_1} \text{ or } 1 + \frac{R_2}{R_1} \tag{1}$$

Assuming resistance values of $R_1 = 1\ k\Omega$ and $R_2 = 100\ k\Omega$ for Figure 22C, Equation 1 yields a voltage gain of:

$$A_C = 1 + \frac{R_2}{R_1} = 1 + \frac{100\ k\Omega}{1\ k\Omega} = 1 + 100 = 101$$

Thus, the closed-loop gain depends upon the feedback resistance, and can be set to any value greater than 1 by varying the resistance values. Input impedance is infinite and output impedance is zero. This configuration is used in applications that call for voltage gain with no signal inversion.

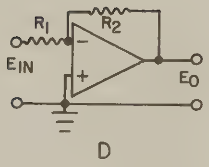


Figure 22

The **INVERTING CONFIGURATION** of Figure 22D is the most commonly used configuration. The feedback is applied through R_2 to the inverting input, and the input signal is applied through R_1 to the same input. Again assuming no current into the (−) input and no difference of potential between the (−) and (+) inputs, the junction of R_1 and R_2 is effectively at ground. This places R_1 across E_{IN}, and R_2 across E_O. The ratio of E_O to E_{IN} is equal to the ratio of R_2 to R_1. The closed-loop gain for this configuration is:

$$A_C = -\frac{R_2}{R_1} \tag{2}$$

The minus sign in this term indicates the signal inversion.

Using Equation 2 and assuming resistance values of $R_1 = 1\,k\Omega$ and $R_2 = 100\ k\Omega$ in the circuit of Figure 22D, the closed-loop gain would be:

$$A_C = -\frac{R_2}{R_1} = \frac{100\ k\Omega}{1\ k\Omega} = -100$$

With R_1 effectively across the signal source, the input impedance of the inverting configuration cannot be infinite. It is the resistance of R_1 (for example, 1 kΩ in the calculation above). However, the output impedance is still essentially zero. This configuration is popular because the gain and input impedance can be matched to the application by simply changing the feedback resistance ratio.

Practical Operating Characteristics

The characteristics of the "ideal" amplifier are, of course, impossible to achieve in practice. However, they give us an idea of the ranges of characteristics desirable in practical op amps. For example, the open-loop gain, although it can never be infinite, should be as high as possible so that the feedback components will exercise a high degree of control over the operation. Open-loop voltage gains of 10,000 to over 1,000,000 are not uncommon. This gain is usually specified at 25°C, with no load, at dc or some low frequency, and with specific power supply voltages.

The gain of an operational amplifier varies with frequency because of the capacitance that exists within the integrated circuit components. The curve of Figure 23 shows a typical plot of open-loop gain versus frequency. As illustrated, gain is essentially constant from dc to approximately 100 Hz, at which point it has dropped to 3 dB below its dc level. There is a characteristic rolloff at a rate of 6 dB per octave between the 3-dB point and the unity gain point at 1 MHz. The unity gain point is considered to be the maximum frequency limit of the amplifier.

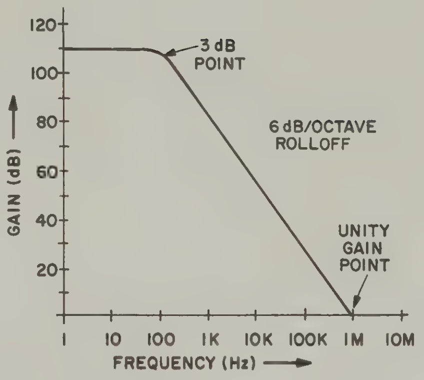


Figure 23

Figure 24 shows the effect of feedback on the gain of the amplifier. A closed-loop voltage gain of 100 is assumed. Notice that the gain is "flat" over a wider frequency range (increased bandwidth), but still decreases to the unity gain crossover point at the same frequency (1 MHz), as determined by the open-loop characteristics of the amplifier.

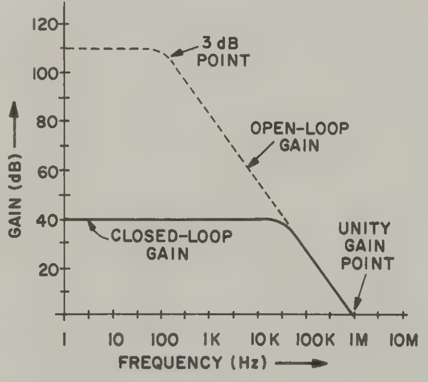


Figure 24

Both the 3-dB point and the unity gain crossover point are significant in the frequency response curve. The 3-dB point is generally referred to as the maximum frequency at which uniform amplification can be achieved. Beyond this point, the output voltage swing is limited by the rolloff of the response curve. However, an operational amplifier can provide useful operation in many applications as long as it provides a gain above unity. Therefore, the unity gain point is an important specification.

In addition to its effect on circuit gain, the internal circuit capacitance produces phase shift of the signal passing through the amplifier. This phase shift, which increases with frequency, adds to the 180° phase shift produced by the feedback network when the op amp is used in a closed-loop configuration. If the total phase shift (feedback plus internal) reaches 360°

before the gain drops below unity, the circuit becomes unstable and breaks into oscillation because the negative feedback has become positive feedback.

COMPENSATING NETWORKS are used to control the phase shift and thus improve the stability of the amplifier. In some op amps, the compensation is designed into the circuit. In others, the user must add external resistors and capacitors at designated terminals to provide the desired compensation. In this latter case, the manufacturer recommends appropriate compensating components in the specification sheet for the amplifier.

We assumed an infinite input impedance and zero output impedance for the ideal operational amplifier. In practice, input impedances range anywhere from several thousand ohms to over a million megohms. The open-loop input impedance depends largely upon the type of input circuitry used in the first stage of the amplifier. Typical output impedances range from less than 10 ohms to several thousand ohms, but in most cases are between 100 and 200 ohms. Output impedance depends mainly upon the type of circuit used in the output stage.

The input stage of an op amp is a differential amplifier, so it is subject to the same characteristics described earlier for differential amplifiers. Input bias current, offset effects and common mode rejection ratio are important factors. If anything, they are more critical in the operational amplifier because the errors that they produce are magnified by the high gain of the amplifier.

In listing the characteristics of the ideal operational amplifier we suggested that the response time of the amplifier should be zero. In other words, if an instantaneous change in input signal occurs, the output signal should change instantaneously to follow it. The maximum rate at which the output can change is referred to as the **SLEW RATE** of the amplifier, expressed in volts per microsecond (V/μs).

High slew rates are desirable if the output voltage excursions are relatively large—for example, if the output must change rapidly from a negative peak to a positive peak in a pulse amplifier application. Unfortunately, slew rate is affected adversely by the compensation applied to the amplifier. Slew rate of an uncompensated op amp may be several volts per microsecond, but this may drop to a fraction of a volt as compensating networks are added. Choice of compensating components is often a compromise between stability and slew rate. Also, the slew rate decreases at higher frequencies because the maximum swing of output voltage is limited by the decreasing gain characteristic of the amplifier.

Typical Operational Amplifiers

We have considered the operational amplifier as a functional element. However, an operational amplifier is actually a multistage device as illustrated by the block diagram of Figure 25. The first stage is a differential amplifier which provides most of the gain of the circuit. The second stage (intermediate stage) is usually another differential amplifier driven by the output of the first differential amplifier. In most circuits, a single output is taken from this second stage.

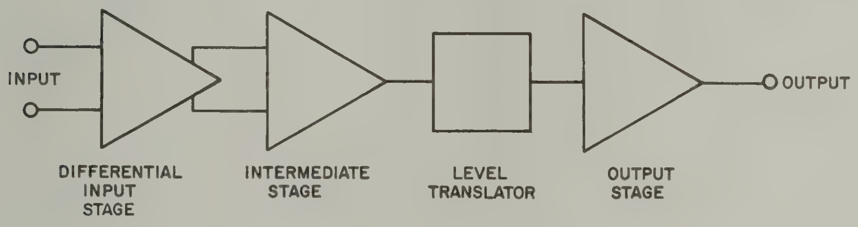


Figure 25

Because direct coupling is used, the dc level rises from stage to stage. A dc component is undesirable because it tends to shift the operating points of the succeeding stages and thereby distorts the signal. A **LEVEL TRANSLATOR** is therefore included to shift the dc level downward. The final stage is usually a push-pull output stage.

The schematic diagram of the 709, a typical operational amplifier, is shown in Figure 26. This unit is a high gain, stable amplifier that has become one of the standards of the industry. Its open-loop characteristics are typical of high performance op amps. For power supply voltages between ±9V and ±15V, it provides a typical open-loop voltage gain of 45,000. The input impedance is typically 150 kΩ and the output impedance 150Ω. The high input impedance limits the input bias current to about 100 nA. Input offset voltage is about 0.6 mV, and input offset current about 10 nA. Common mode rejection ratio is 110 dB. It is capable of an output voltage swing of ±14V at a supply voltage of ±15V. Slew rate varies from over 10 V/µs to less than 1 V/µs as the degree of phase compensation is increased.

Referring to Figure 26, Q_1 and Q_2 form the input differential amplifier, receiving the inverting and noninverting inputs from pins 2 and 3. Q_{11} serves as the constant current source for this stage. Diode-connected transistor Q_{10} serves as a bias stabilizer for Q_{11}. The collectors of Q_1 and Q_2 are direct coupled to the two Darlington pairs (Q_3Q_5 and Q_4Q_6) that form the second differential amplifier. Diode-connected transistor Q_{15} and resistors R_3 and R_4

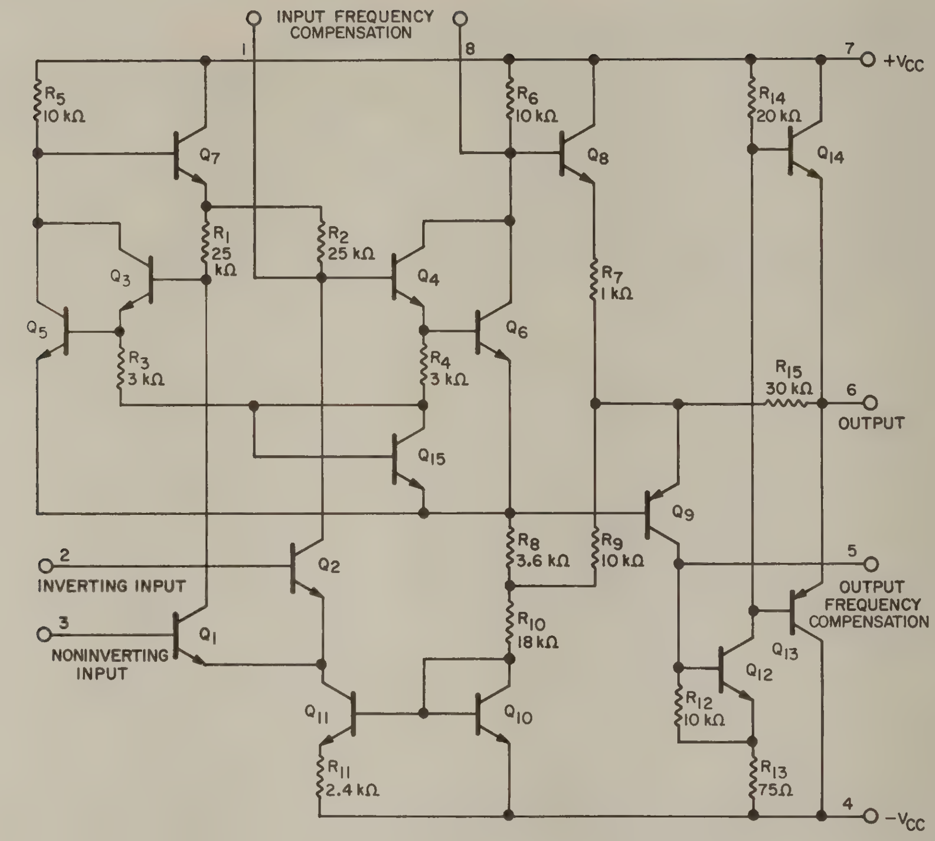


Figure 26

aid in biasing this stage and Q_7 tends to stabilize the operating point for various supply voltages.

The single-ended output of the second stage is taken from the Q_4Q_6 collector and fed to emitter follower Q_8. Q_8 isolates the differential amplifier from the output stage, and also provides level translation to compensate for the rise in dc level through the direct-coupled stages. The emitter signal of Q_8 is applied, through Q_9, to the base of Q_{12}, which is the driver for the output stage. The collector signal of Q_{12} is applied to the bases of Q_{13} and Q_{14}, which form a complementary symmetry output stage. The output is taken at pin 6.

PNP transistor Q_9 provides additional level translation, sensing any shift in output stage level via feedback resistor R_{15} and changing its collector-emitter voltage to restore the proper dc operating level. Feedback is returned from the output stage to the emitter of Q_9 through R_{15} to improve the linearity of operation.

The dc supply is connected between pin 7 ($+V_{CC}$) and pin 4 ($-V_{CC}$). The maximum supply voltage is ±18 volts, with a recommended range of ±9 to

±15 volts. Input compensation is applied to pins 1 and 8. Output compensation is applied to pins 5 and 6. The compensating networks are illustrated in Figure 27. The 50Ω resistor at the output of the amplifier is used as a current-limiting resistor to protect the output stage against overloads.

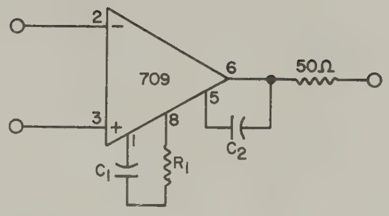


Figure 27

The curves of Figure 28 show the effects of various combinations of compensating components on the open-loop frequency response. In general, increasing the amount of compensation causes a decrease in open-loop voltage gain, but results in a more linear rolloff that improves stability at high frequencies. Figure 29 shows the effect of these same compensating networks on the output voltage swing at various frequencies. As indicated, the greater the amount of compensation, the smaller the output voltage swing at higher frequencies.

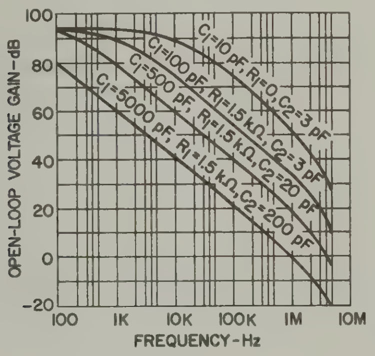


Figure 28

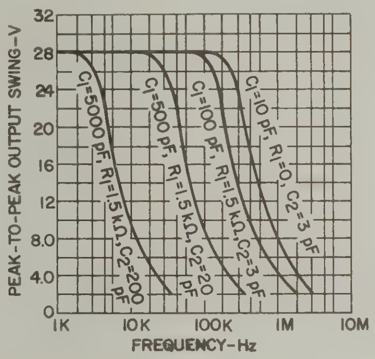


Figure 29

Figure 30 shows the voltage transfer characteristic of the 709 at a supply voltage of ±15 volts and a load resistance of 10 kΩ. The large slope of this curve is an indication of the high open-loop gain of the amplifier. Notice that the curve is also very linear to practically the full value of supply voltage, demonstrating the linearity and large output voltage swing capability of the circuit.

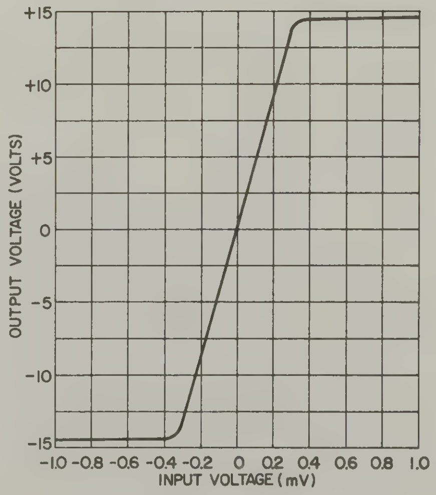


Figure 30

Another op amp that has become an industry standard is the 741, shown schematically in Figure 31. This is one of a number of units that features internal compensation. A 30 pF capacitor is fabricated on the chip to provide the desired phase control at high frequencies.

In Figure 31, the input differential amplifier consists of Q_1 and Q_2 augmented by Q_3 and Q_4 and a controlled current source consisting of Q_5 and Q_6. Bias current for this circuit is provided by a constant current source consisting of Q_9 and Q_{10}, which supplies constant base current to Q_3 and Q_4 to establish the operating current for the differential stage. The base potentials of Q_9 and Q_{10} are stabilized by diode-connected transistors Q_8 and Q_{11}. Q_4 is an

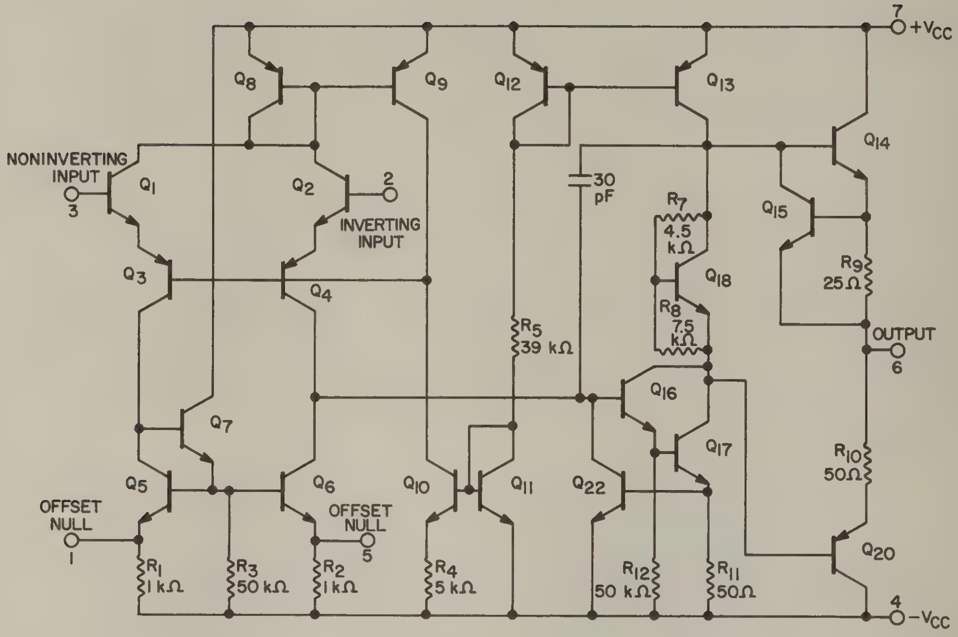


Figure 31

ordinary transistor with its base connected to the Q_3 base and the collectors of Q_9 and Q_{10}. Many transistors in IC's are drawn this way.

PNP transistors Q_3 and Q_4 increase the maximum input signal capacity of the differential stage. The base-emitter junctions of Q_3 and Q_4 are in series with the base-emitter junctions of Q_1 and Q_2, respectively. An input signal would have to break down both of the series junctions in order to overload the stage. The stage is practically indestructible at the signal levels normally encountered.

The bias currents for both Q_5 and Q_6 are supplied through Q_7, and must therefore be equal at all times. Q_7 is controlled by the collector voltage of Q_5. Any change in Q_5 collector voltage produces identical changes in Q_5 and Q_6 collector currents by virtue of the equal changes in base current caused by Q_7. For example, if the collector current of Q_5 increases by a given amount, the collector current of Q_6 will increase by this same amount.

Suppose that a differential input signal causes the collector current of Q_1 (and Q_3 and Q_5) to increase, and the collector current of Q_2 (and Q_4) to decrease. The action of Q_7 causes the base current of Q_6 to increase. As a result, the Q_6 collector current increases by the same amount as the Q_5 collector current increases. Since the current through Q_2 (and Q_4) has decreased, and the current through Q_6 has increased by the same amount, the net change in current at the junction of Q_4 and Q_6 is twice that of Q_2

alone. The signal at this point is the output of the differential stage. From this action, we see that Q_4 and Q_6 act as a complementary-symmetry amplifier whose output voltage is proportional to the difference of the inputs to the Q_1 and Q_2 differential amplifier.

This output is fed to a Darlington pair consisting of Q_{16} and Q_{17}, which serves as a driver for the output stage. Q_{16} and Q_{17} are also part of a level translator which includes constant current source Q_{13} (stabilized by diode-connected transistor Q_{12}) and a network consisting of R_7, R_8 and Q_{18}. This network is designed so that the voltage changes across the various transistor junctions provide a zero dc level in the output stage when no signal is applied to the input.

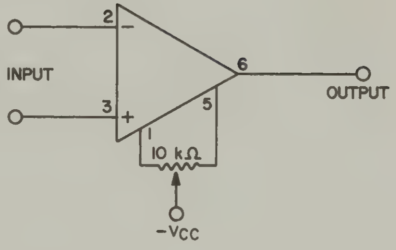


Figure 32

The driver stage supplies the signal for complementary output transistors Q_{14} and Q_{20}. Output overload protection is provided by Q_{22} and Q_{15}. If the load current exceeds the safe limit, the voltage drop across R_9 and the voltage drop across R_{11} forward bias the emitter junctions of Q_{15} and Q_{22}, respectively, and these transistors turn on. This decreases the Q_{16} and Q_{14} base voltages, which turns off the output stage.

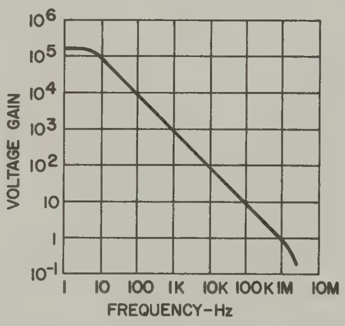


Figure 33

Although the input circuit is designed to have very low offset, provision is made for an external offset nulling arrangement that will completely eliminate offset for critical applications. The nulling circuit is shown in Figure 32. A 10 kΩ potentiometer is connected between the emitters of Q_5 and Q_6 through pins 1 and 5, with the negative power supply connected to the movable contact of the potentiometer. By varying the setting of the null pot, the emitter potentials of Q_5 and Q_6 can be varied to compensate for any imbalance in the two legs of the differential amplifier. Offset adjustment range is approximately ±15 mV.

Typical open-loop voltage gain for the 741 IC is 200,000. It features an input impedance of about 2 megohms and an output impedance of 75Ω. Input bias current is typically 80 nA, with input offset current of 20 nA and offset voltage of 1 mV. Typical slew rate is 1 V/μs or less.

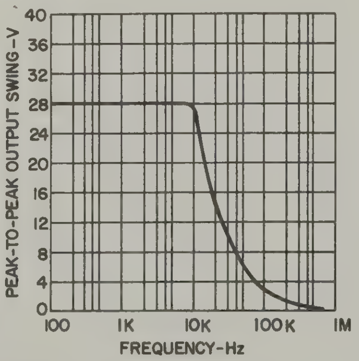


Figure 34

The gain-frequency relationship of the 741 IC is illustrated in Figure 33, and the output voltage swing-frequency relationship in Figure 34. These two characteristics and also the slew rate are permanently limited by the internal compensation of the amplifier. In comparison, the upper frequency limit, output signal swing, and slew rate of a noncompensated amplifier such as the 709 can be optimized by reducing the amount of compensation.

One more example of operational amplifier design is the 740 IC shown in the simplified schematic diagram of Figure 35. The circuitry is essentially the

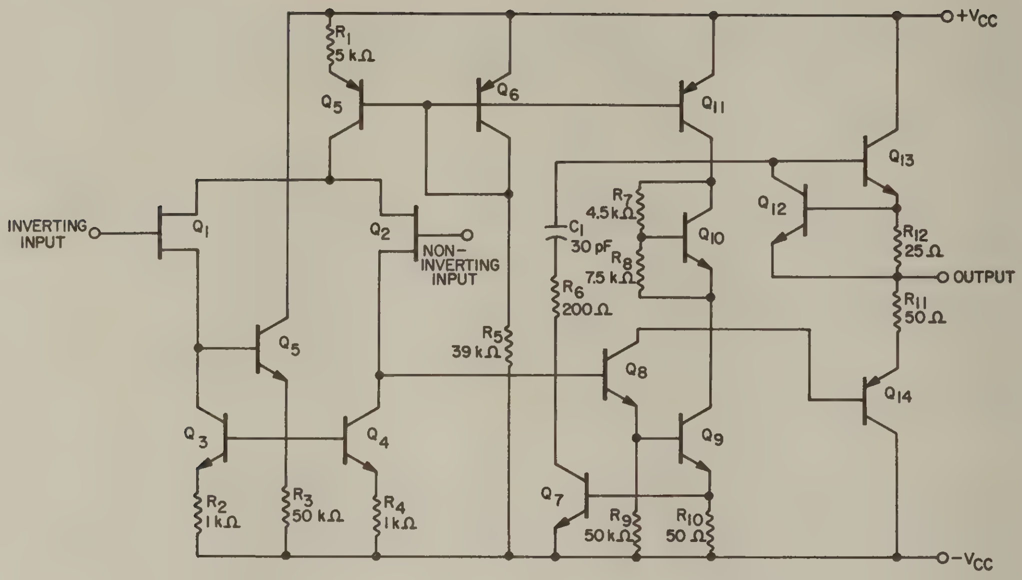


Figure 35

same as that of the 741 except for the modification of the differential input stage to include junction FET's in place of the NPN and PNP junction transistors. This IC capitalizes on the high input impedance of the FET to provide low input bias current and offset current.

Typical input bias current for the 740 is 0.1 nA, with an input offset current of only 0.04 nA, because of its exceptionally high input impedance of about 1,000,000 megohms ($10^{12}\Omega$). Open-loop voltage gain is typically high, around 1,000,000.

However, typical input offset voltage is about 10 mV, higher than that of the 741. Typical slew rate is 6.0 V/μs. All other characteristics are essentially the same as those of the 741. The gain characteristics and the output voltage swing are illustrated in Figures 36 and 37.

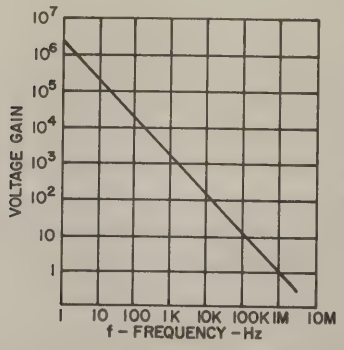


Figure 36

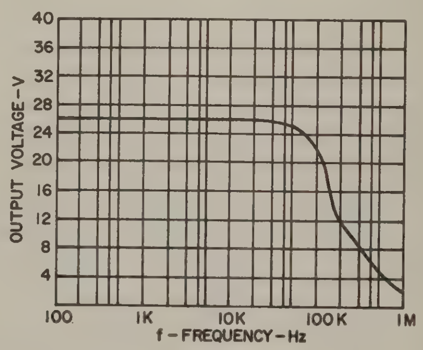


Figure 37

The following Practice Exercise questions cover the subjects which you have just studied. They are:

OPERATIONAL AMPLIFIERS

STANDARD CONFIGURATIONS

PRACTICAL OPERATING CHARACTERISTICS

TYPICAL OPERATIONAL AMPLIFIERS

18. What effect do emitter resistors R_4 and R_5 have on the operation of the differential amplifier of Figure 7?

19. Emitter followers Q_1 and Q_5 are used in Figure 7 to provide a low impedance input. True or False?

20. In the circuit of Figure 16, a cascode stage is formed by transistors ____ and ____.

21. For maximum gain in the circuit of Figure 16, the AGC voltage should be (a) maximum, (b) minimum.

22. When the MC1550 is operated as a differential amplifier, what is the function of Q_1?

23. Basically, what is an operational amplifier?

24. The operation of an op amp is controlled by (a) positive feedback from the output to the input, (b) negative feedback from the output to the input.

25. A signal applied to the (−) input of the operational amplifier represented in Figure 21 will produce an output signal that is (a) in phase, (b) inverted.

26. In the open-loop configuration, the gain of an op amp is determined by the feedback components. True or False?

27. The gain of a voltage follower is (a) zero, (b) 1, (c) infinite.

28. The gain of the noninverting op amp of Figure 22C is determined by the relative values of R_1 and R_2. True or False?

29. If the resistance of R_2 is 10 times larger than that of R_1 in Figure 22D, what is the gain of the amplifier?

30. What determines the input impedance of an inverting op amp?

31. For stable operation, the phase of the feedback signal in a closed-loop operational amplifier must not reach 360° before the gain drops to unity. True or False?

32. The stability of an operational amplifier is improved and the phase shift controlled by using _______________ ____________.

33. The input and output impedances vary from amplifier to amplifier, but in general the input impedance of an operational amplifier is (a) high, (b) low.

34. The output impedance of an operational amplifier is (a) high, (b) low.

35. The slew rate of an operational amplifier is an indication of how quickly the output can change to follow a change in input signal. True or False?

36. What is the purpose of a level translator in an operational amplifier?

37. As illustrated by the curves of Figure 28, increasing the amount of compensation causes a decrease in open-loop voltage gain, but also causes a more linear rolloff in gain. True or False?

38. What effect does phase compensation have on the maximum output voltage swing?

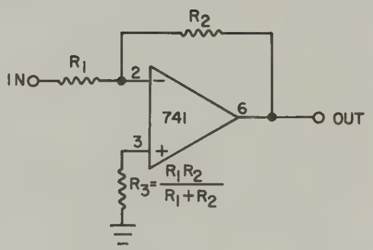
39. Compared to the NPN and PNP transistor input of the 741 op amp, the FET input of the 740 provides (a) higher input impedance, (b) lower input impedance, (c) the same input impedance.

OPERATIONAL AMPLIFIER APPLICATIONS

Operational amplifiers are the most versatile of all linear integrated circuits. They have almost unlimited applications in all types of electronic systems. We have selected a number of op amp applications to illustrate this versatility. In the following examples the op amps are considered as functional elements adapted to the application by the external circuitry. Bias supply connections are omitted for simplicity.

Amplifier Circuits

The basic amplifier configurations for an operational amplifier are illustrated in Figures 38 and 39. The inverting amplifier is shown in Figure 38A, with a table of resistance values to produce typical closed-loop gains. The gain is equal to the feedback resistance (R_2) divided by the series input resistance (R_1). The input impedance of the amplifier is equal to the value of R_1. To minimize offset, the value of R_3 is chosen to equal the equivalent parallel resistance of R_1 and R_2.



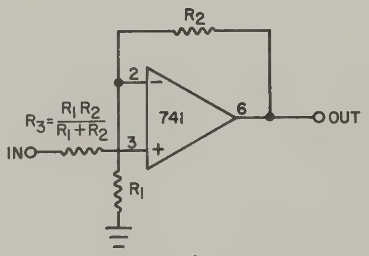
A

R1	R2	GAIN
1K	10K	10
1K	100K	100
100	100K	1000

B

Figure 38

Figure 39A is the basic noninverting amplifier. Here the input signal is applied to the noninverting input and the feedback is applied to the inverting

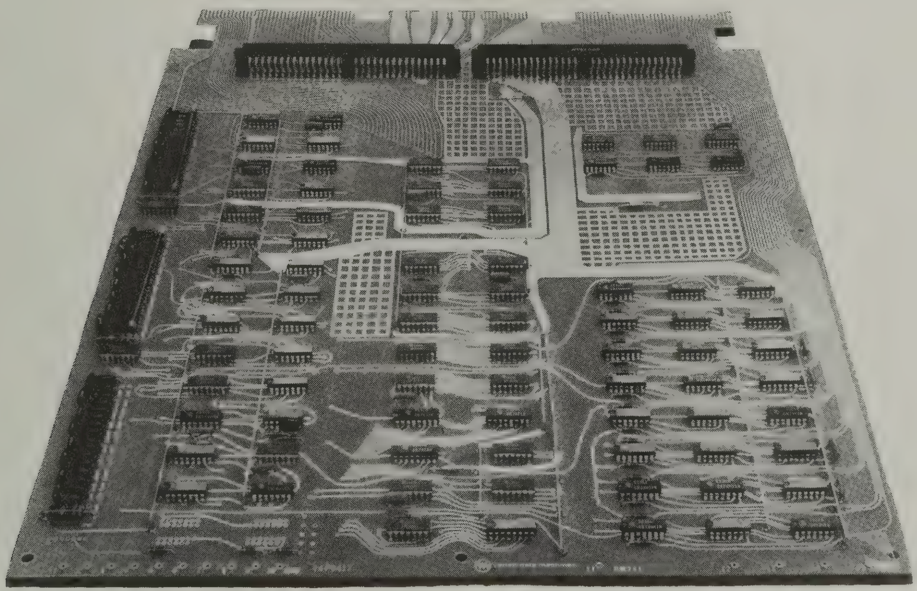


A

R1	R2	GAIN
1K	9K	10
100	9.9K	100
100	99.9K	1000

B

Figure 39



A plug-in printed circuit card can accommodate many integrated circuit packages, permitting hundreds or even thousands of circuits to be used on one card.
Courtesy Varian Data Machines

input. The gain is equal to ($R_1 + R_2$) divided by R_1 (or $1 + R_2/R_1$). Again, the value of R_3 is selected to equal the parallel resistance of R_1 and R_2 to minimize the offset. The typical resistance values in Figure 39B result in the degrees of gain shown in the table. The input impedance of this circuit is related to the open-loop input impedance of the op amp.

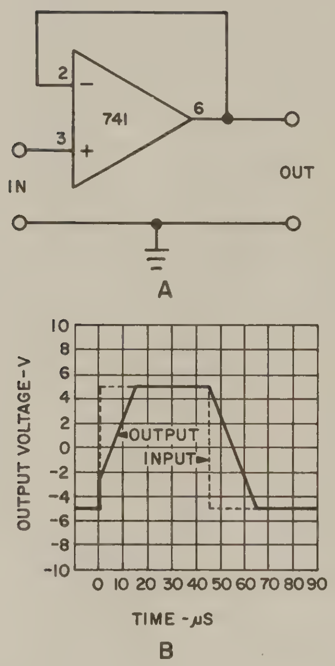


Figure 40

Figure 40A is an example of the voltage follower (or unity voltage gain amplifier). The output is fed back directly to the inverting input, and the input signal is applied to the noninverting input. As the name implies, in this circuit the output voltage "follows" the input voltage in amplitude and phase. Since the circuit operates with unity voltage gain, the output waveform is theoretically an exact replica of the input waveform. However, as indicated by the waveforms in Figure 40B, the output waveform actually obtained can be distorted by the effects of the internal circuit capacitance.

The voltage follower features the highest input impedance and lowest output impedance of all op amp configurations. For the 741 op amp illustrated in Figure 40, typical input impedance is 400 megohms, and output impedance is less than 1Ω. Even though the voltage gain is no greater than unity, this arrangement is useful as a buffer or isolating stage, and is capable of producing a relatively high output current.

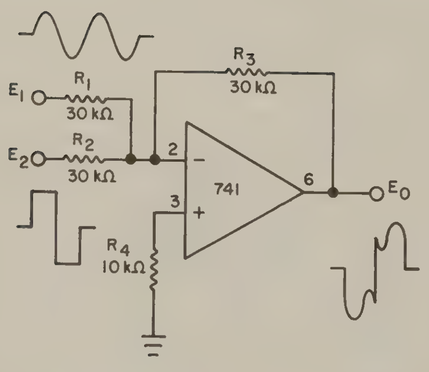


Figure 41

The inverting amplifier can be used as a summing amplifier, or adder, as shown in Figure 41. Here we have applied two signals to the inverting input. One input is a sinewave with twice the frequency and half the amplitude of the other input which is a square wave. The resulting output is the sum of the instantaneous values of the two signals, inverted by the normal inverting action of the amplifier.

The summing action is made possible by the fact that the inverting input of the op amp is held very near ground potential by the negative feedback. The input signals are effectively isolated from each other since they are effectively grounded at the input of the amplifier and each one is treated by the amplifier as an independent input signal. However, the amplified signals appear simultaneously in the output.

The summing amplifier circuit adds the input voltages (referred to as E_1 and E_2 in Figure 41) algebraically. Each input voltage is amplified by a factor equal to the ratio of the feedback resistance (R_3 in Figure 41) to its input resistance (either R_1 or R_2). The output voltage may be determined by using the following equation:

$$E_O = -\left[\left(\frac{R_3}{R_1}\right)E_1 + \left(\frac{R_3}{R_2}\right)E_2\right] \tag{3}$$

This equation states that the output voltage (E_O) is equal to the sum of the individual input voltages (E_1 and E_2) which are multiplied by the ratios R_3/R_1 and R_3/R_2. The negative sign is added to the right side of the equation to show that the amplifier inverts the input signals.

In Figure 41, the feedback and input resistors are equal in value; therefore, each input voltage receives a gain of 1. This means that the output signals are simply added together without additional amplification. However, the output voltage equation shows that an amplified output can be obtained by making the feedback resistor larger than the input resistors. If the input resistors were unequal, a "weighted" sum would be obtained. That is, the signal fed through the smaller input resistor would receive a greater amount of amplification. A circuit arranged in this way is referred to as a **SCALING ADDER.**

Additional inputs can be provided up to the practical current input level and maximum output signal swing of the amplifier. Notice that the noninverting input resistor (R_4) is selected so that its value is equal to the equivalent parallel resistance of the feedback resistor and all inverting input resistors. This ensures that the + and − input currents are approximately equal, thus keeping the offset error voltage to a minimum.

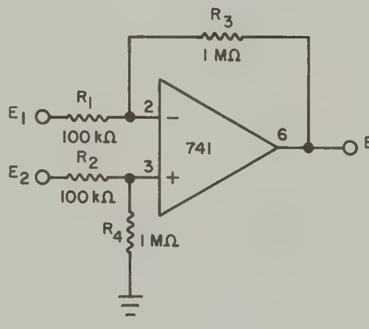


Figure 42

The circuit used as a differential amplifier is shown in Figure 42. This complete circuit functions as a conventional differential amplifier, with an output that is proportional to the difference between the two inputs. This circuit is usually constructed so that R_1 is equal to R_2 and R_3 is equal to R_4. This means that the ratio R_3/R_1 will be equal to the ratio R_4/R_2. Under these conditions the output voltage (E_O) will be equal to the difference between the input voltages (E_1 and E_2) multiplied by the gain of the amplifier which is equal to the ratio R_3/R_1. When expressed as an equation, the output voltage is equal to:

$$E_O = \frac{R_3}{R_1}(E_2 - E_1) \tag{3a}$$

With the values shown in Figure 42, the circuit provides a gain (R_3/R_1) of 10.

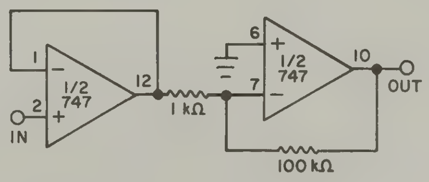


Figure 43

One final example of an operational amplifier circuit is shown in Figure 43. This circuit consists of a cascade of two direct coupled operational amplifiers. Notice in particular that each stage is labeled 1/2 747. The 747 integrated circuit is actually two 741 op amps fabricated on a single chip but isolated from each other so that they function independently. The practice of manufacturing multiple units such as this is becoming very popular because of the savings in space of the single package as compared to two separate packages, and also because of the close match that can be provided between the individual amplifiers. The 747 is referred to as a "dual op amp."

Combinations of four op amps are also produced. These are referred to as "quad op amps."

Getting back to the circuit of Figure 43, the input stage is connected as a voltage follower. This provides a high impedance input, in this case about 200 megohms, which minimizes loading of the signal source. The second stage is an inverting amplifier that provides the desired voltage gain. As we can see from the feedback-to-input resistance ratio (100 kΩ to 1 kΩ), the gain is 100. Thus, the output (inverted) at pin 10 is 100 times the input at pin 2. The high input impedance and reasonably high gain make this type of circuit ideal for applications such as instrumentation amplifiers.

Waveshaping Circuits

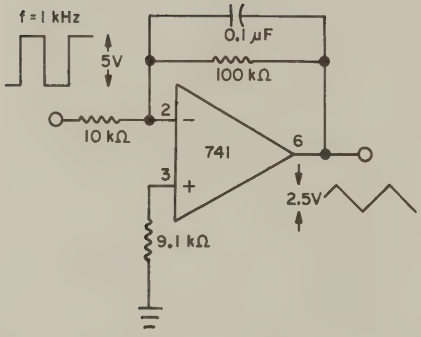


Figure 44

Operational amplifiers are often used to form active waveshaping networks. Examples of these applications are the integrator circuit of Figure 44 and the differentiator circuit of Figure 45. These circuits are essentially inverting amplifiers with capacitors in place of resistors in the feedback or input circuit.

In the integrator of Figure 44, the capacitor is in the feedback loop. The charging current of the capacitor is the current in the input resistor, and the output voltage is the voltage across the capacitor. The gain of the circuit depends on the reactance of the feedback capacitor at the frequency of the input signal.

When a square wave is applied to the input of the circuit as shown, the capacitor attempts to charge to the peak value of the square wave on each alternation. With a signal frequency of 1 kHz and the component values shown, the capacitor and input resistor effectively have a time constant that is long when compared with the period (time for one cycle) of the input waveform. When the input square wave jumps to its positive peak value, the capacitor tries to charge to this value but cannot because of its relatively long time constant. When the input square wave voltage drops to its negative peak value the capacitor discharges and tries to charge to the negative peak voltage. The voltage across the capacitor therefore increases and decreases linearly and a triangular waveform is produced at the output of the circuit.

The 100 kΩ resistor across the capacitor prevents the circuit from integrating the dc offset voltage at the input of the op amp, which would otherwise build up across the capacitor over a period of time. At the frequencies for which the circuit is designed (1 kHz in this case), the resistor does not have adverse effects on circuit operation.

In the differentiator circuit of Figure 45, the component values have been selected to permit high amplification of the ac input signal. Because there is little negative feedback, any small signal of a repetitive nature, such as the triangle wave shown at the input, will drive the amplifier between full cutoff and saturation.

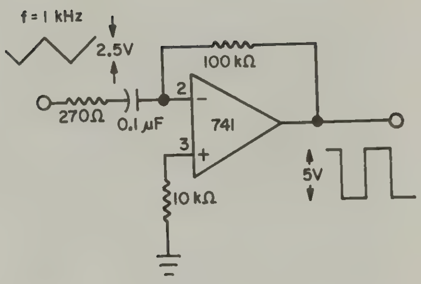


Figure 45

Noise spikes can be a serious problem with high-gain amplifiers because they represent rapid changes which produce large pulses of output voltage. At high frequencies, the impedance of the 0.1 μF capacitor is negligible. Therefore, the 270Ω resistor limits the high-frequency gain of the circuit so that noise pulses do not receive excessive amplification.

Active Filters

Operational amplifiers are commonly used with RC networks to produce various types of filters. The RC networks control the gain of the op amps at various frequencies to provide the filter action. Active filters are particularly useful at lower frequencies, where inductors required to produce comparable filter action would be large and cumbersome. Op amps are also desirable because the gain of the op amp can overcome the losses usually associated with filter circuits.

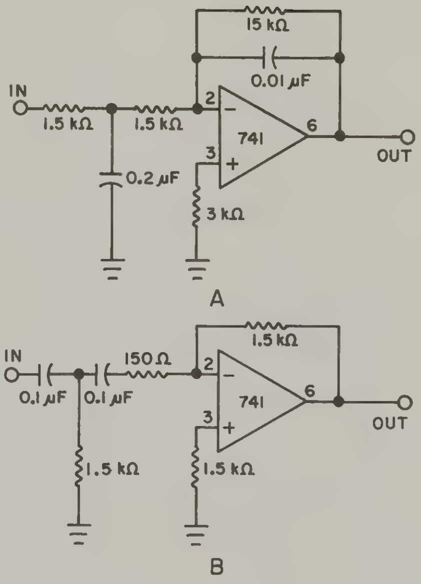


Figure 46

Examples of active filters are the low-pass filter of Figure 46A and the high-pass filter of Figure 46B. In the low-pass filter, a capacitor is used as a shunt element in the inverting input of the operational amplifier. At high frequencies the reactance of the capacitor is low, and very little of the input signal is applied to the amplifier input. At low frequencies the reactance is high, and the input signals are amplified with little attenuation.

The opposite action occurs in the high-pass filter of Figure 46B. The capacitive elements are in series with the inverting input, and therefore, they attenuate the input signal at low frequencies. At high frequencies the reactance is low and the input signal is passed to the amplifier with little attenuation.

The cutoff frequency for both circuits of Figure 46 depends on the relative values of resistance and capacitance. The values indicated in the diagram produce a cutoff at a little over 100 Hz. The gain of the filter depends on the ratio of feedback impedance to series input impedance. The 0.01 μF capacitor in the feedback loop of the low-pass filter of Figure 46A prevents integration of the offset voltage. The 150Ω resistor in series with the inverting input of the high-pass filter of Figure 46B stabilizes the circuit against high-frequency noise pulses.

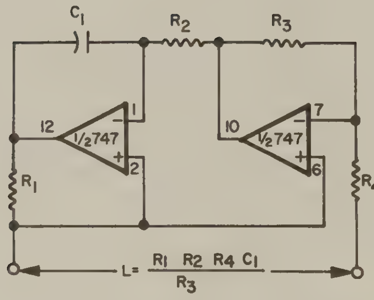


Figure 47

A circuit that is especially useful in filter design is illustrated in Figure 47. This circuit, referred to as a **GYRATOR**, has the unique ability to simulate the property of an inductor. The two halves of a 747 dual op amp are interconnected through a network of resistors and capacitors to produce a reactance that decreases with frequency between the circuit terminals. The simulated inductance can be calculated as indicated in the diagram, where L is in henries, R in ohms and C in farads.

Figure 48 shows a conventional high-pass filter using a gyrator as the shunt inductive element. Gyrators are used in filters of this type, and as the shunt element in bandpass and other types of filters. However, they are uncommon in low-pass applications because one side of the gyrator must be grounded, as shown in Figure 48.

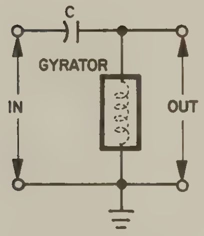


Figure 48

Comparators

An operational amplifier can be used as a comparator by connecting one of its input terminals to a reference voltage and applying the input signal to the other input terminal. The op amp "compares" the input signal to the reference, and the op amp output then depends on whether the input signal is positive, negative or equal to the reference potential.

Figure 49 illustrates a comparator circuit with a reference potential of +1 volt on the inverting point. The op amp is operated open loop, so that even a very small differential input will cause the amp to go into saturation. If the input signal is equal to the reference voltage (no differential input), the output is zero. If the input is greater than the reference, the op amp is driven to positive saturation. If the input is less than the reference, the op amp is driven to negative saturation.

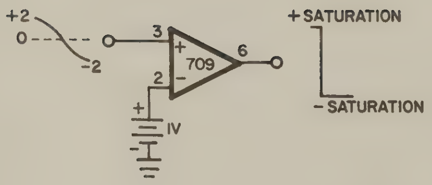


Figure 49

In the circuit of Figure 49, with the input shown, the output is at positive saturation from +2 volts of input until the input drops to the +1 volt level. The output then goes to zero, then to negative saturation as the input continues below the +1 volt level. For the 709 op amp shown, assuming a ±15 volt supply, the saturation levels would be typically ±14 volts.

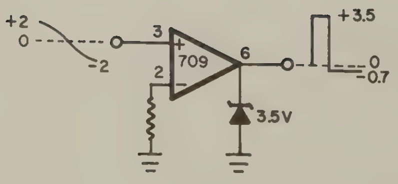


Figure 50

Figure 50 shows a comparator with a zero reference (the inverting input is returned to ground), and with a zener diode connected to the output. The zener diode limits the level of the output signal. When the op amp goes to positive saturation the zener diode limits the positive peak to 3.5 volts. For negative saturation, the output is clamped at the forward voltage drop of the diode, approximately 0.7 volt. This provides an output that is compatible with digital logic levels.

A comparator with a zero reference is used to sense the output of a magnetic pickup in Figure 51. The magnetic pickup is serving as a generator in a tachometer system. The sinewave output is applied to the noninverting input of the op amp. Each time the sinewave passes through zero, the output of the op amp switches, as indicated by the waveforms in the diagram. This circuit is referred to as a **ZERO CROSSING DETECTOR.** Each output pulse of a given polarity indicates one cycle of input, which in this case corresponds to one rotation of the element.

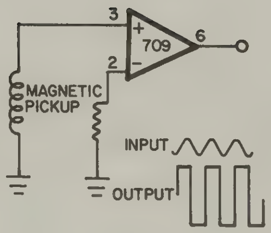


Figure 51

In comparator applications, the op amp should exhibit a high slew rate if the output voltage must change rapidly from the maximum positive level to the maximum negative level. Because slew rate is adversely affected by phase compensation, an uncompensated op amp such as the 709 is preferred to a compensated op amp for this application. The op amp is operated without feedback, so that compensation is not required.

Analog Storage Elements

The circuit of Figure 52 is an example of how an operational amplifier can be used as a temporary storage device. This is called a **SAMPLE AND HOLD CIRCUIT.** It includes a switching arrangement that applies the input signal to a capacitor on command from an external control circuit. During the time that the switch is closed (the sampling time), the capacitor charge varies with the input signal voltage. When the switch is opened, the capacitor remains charged to the signal voltage that was present at the end of the sampling interval.

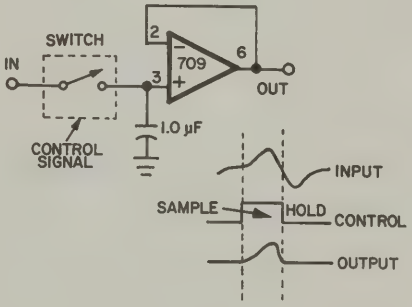


Figure 52

The capacitor used in this circuit must have very low leakage so that it will hold its charge for a reasonable length of time. The voltage follower, with its high input impedance, serves as a buffer to prevent the charge from leaking off rapidly through the load. The "switch" must also represent a high impedance to isolate the capacitor from the source during the nonsampling intervals. Reed relays are sometimes used for this purpose. An FET connected source-to-drain in series with the input, with the gate controlled by the command signal, is another popular switch element. Holding times up to several hours are possible with this type of circuit. Thus, a carefully designed sample and hold circuit can be used as a storage element in an analog memory circuit.

ARRAYS

Another approach to IC design is the **ARRAY**, a combination of independent components or amplifier stages on a single chip. The circuit designer interconnects the elements of the array with discrete external components to form the desired circuit. The near perfect match of electrical and thermal characteristics of the components in the array makes it particularly useful in designing balanced circuits or systems.

Typical arrays are illustrated in Figure 53. The CA3019 diode array of Figure 53A consists of two unconnected silicon diodes and a diode quad connected in a bridge configuration. This array can be used wherever closely matched diodes are required. The bridge arrangement is especially useful for circuits such as bridge rectifiers, balanced modulators and so on. Terminals 2 and 6 can be shorted to convert the bridge to a set of two series diodes, if desired. Terminals 5 and 8 can be shorted to provide two sets of back-to-back diodes for limiting or clipping applications.

Figure 53B is a transistor array which contains two independent NPN transistors and two NPN transistors connected for Darlington or emitter-follower operation. In this array, the CA3018, transistors Q_1 and Q_2 can be connected in any of the standard configurations. Pins 11 and 12 can be connected together to form a Darlington pair of Q_3 and Q_4. Also, Q_3 and Q_4 can be connected as separate stages in which Q_3 is used as an emitter follower direct coupled to the base of Q_4.

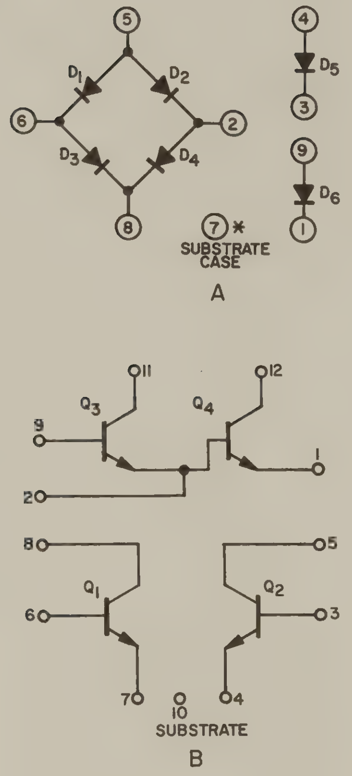


Figure 53

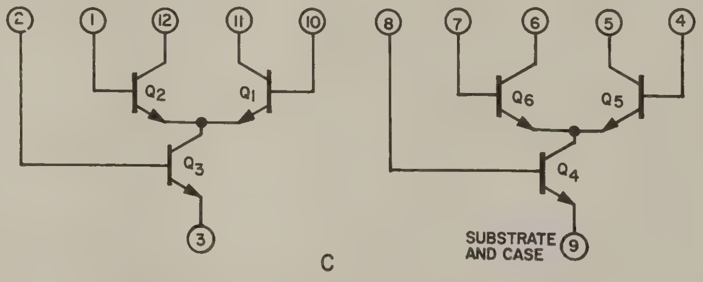


Figure 53

The CA3026 array of Figure 53C consists of two basic differential amplifier stages. Q_1 and Q_2 form the differential pair of one stage, with Q_3 as the constant current source. Q_4, Q_5 and Q_6 form a similar arrangement for the other stage. Cascode operation is also possible, with Q_1 and Q_3 forming the cascode pair and Q_2 as an AGC transistor.

The arrays of Figure 53 are but a few examples of the arrays now available. There are many more combinations of diodes and transistors, including arrays of both NPN and PNP transistors on a single chip. Arrays of FET's and SCR's are also being produced in limited quantity, and may soon become an important part of the linear IC inventory.

The following Practice Exercise questions cover the subjects which you have just studied. They are:

OPERATIONAL AMPLIFIER APPLICATIONS
- AMPLIFIER CIRCUITS
- WAVESHAPING CIRCUITS
- ACTIVE FILTERS
- COMPARATORS
- ANALOG STORAGE ELEMENTS

ARRAYS

40. In either the inverting or noninverting op amp configuration, the gain is increased by making the feedback resistor larger than the input resistor. True or False?

41. How does the input impedance of the voltage follower of Figure 40 compare with the input impedance of the inverting amplifier of Figure 38?

42. The voltage follower provides the highest gain of any op amp configuration. True or False?

43. If the input resistor connected to input 1 in Figure 41 is increased in value, what will happen to the amplitude of the sinewave component in the output waveform?

44. To change a square wave to a triangular wave, the square wave can be fed to (a) an integrator, (b) a differentiator.

45. What is the purpose of the 270Ω input resistor in Figure 45?

46. An operational amplifier circuit that provides the effect of an inductance is called a ____________.

47. When an operational amplifier is used as a comparator, the output is zero when the input voltage is equal to the reference total. True or False?

48. In the comparator of Figure 49, what is the output voltage when the input voltage is less than +1 volt?

49. What is the effect of the zener diode at the output of the comparator of Figure 50?

50. **To provide high slew rates in a comparator application, the op amp should be heavily compensated. True or False?**

51. **In the sample and hold circuit of Figure 52, the op amp is operated as (a) an inverting amplifier, (b) a voltage follower, (c) an open-loop comparator.**

SUMMARY

Linear integrated circuits are now used extensively in many types of electronic equipment. The basic cascode and differential circuit arrangements that are employed in linear IC's are highly versatile and may be used in many applications. The differential amplifier is also an essential part of the operational amplifier which is one of the most widely used circuits in integrated circuit form. The operational amplifier may be used as an active component in the construction of audio or r-f amplifiers, oscillators, waveshaping circuits, filters, comparators, storage devices and many other types of circuits. Integrated circuit arrays are also available which contain a number of individual active and passive components which may be interconnected to form a variety of circuits. Circuits of this type permit complete design flexibility.

IMPORTANT DEFINITIONS

ANALOG CIRCUITS—Circuits in which the electrical signals vary in proportion to the quantities they represent. Also referred to as a LINEAR CIRCUIT.

ARRAY—A combination of independent components or amplifier stages on a single chip.

AUTOMATIC GAIN CONTROL (AGC)—A control system in which a feedback signal is used to automatically adjust the gain of the controlled circuit.

CASCODE AMPLIFIER—An amplifier consisting of a common-emitter stage directly coupled to a common-base stage.

CLOSED-LOOP GAIN (A_C)—The gain of an operational amplifier with negative feedback applied.

COMMON MODE OPERATION—Simultaneous application of signals to both inputs of a differential amplifier.

COMMON MODE REJECTION RATIO (CMRR)—In a differential amplifier, the ratio of common mode voltage gain to differential mode voltage gain. The ability to reject undesired common mode signals.

COMMON MODE VOLTAGE GAIN (A_C)—In a differential amplifier, the ratio of output voltage to the common mode input that causes it.

COMPARATOR—A differential amplifier in which one input is connected to a reference voltage (or ground) and the input signal is applied to the other input. The input signal is therefore "compared" to the reference voltage.

COMPENSATING NETWORKS—RC networks used to control the phase shift and thus improve the stability of an operational amplifier.

DIFFERENTIAL AMPLIFIER—An amplifier consisting of two active elements (i.e., transistors) and their load resistors which form the two legs of a bridge.

DIFFERENTIAL MODE OPERATION—Application of a signal between the two inputs of a differential amplifier.

DIFFERENTIAL VOLTAGE GAIN (A_d)—In a differential amplifier, the ratio of output voltage to the differential input that causes it.

DIGITAL CIRCUITS—Circuits that use off and on states (two different voltage levels) to represent some quantity or operation.

IMPORTANT DEFINITIONS (Continued)

GYRATOR—A combination of operational amplifiers and appropriate resistors and capacitors used to simulate the property of inductance.

INPUT BIAS CURRENT—The average current drawn by the two input circuits of a differential amplifier with no signal applied.

INPUT OFFSET CURRENT—The difference in input currents required to produce zero output voltage in a differential amplifier with no signal present.

INPUT OFFSET VOLTAGE—The difference in input voltages required to produce zero output voltage in a differential amplifier with no signal present.

INVERTING CONFIGURATION—An operational amplifier in which the input signal is applied to the inverting input, and the output is therefore an inverted form of the input, or out-of-phase with the input.

LEVEL TRANSLATOR—A circuit included in an operational amplifier to prevent an undesired shift in dc level due to the direct coupling between stages.

LINEAR CIRCUITS—Circuits in which the electrical signals vary in proportion to the quantities they represent. Also referred to as ANALOG CIRCUITS.

MONOLITHIC PROCESS—A process of fabricating integrated circuits in which all elements are formed on or within a single piece of semiconductor material.

NONINVERTING CONFIGURATION—An operational amplifier in which the input signal is applied to the noninverting input, and the output is therefore in phase with the input.

OFFSET DRIFT—The change in input offset current or voltage due to a change in operating temperature.

OPEN-LOOP CONFIGURATION—An operational amplifier operated without feedback.

OPEN-LOOP GAIN (A_O)—The gain inherent to an operational amplifier. This is the gain it provides with no feedback applied.

OPERATIONAL AMPLIFIER—A high gain, direct-coupled amplifier capable of performing some desired operation as determined by its external circuitry, in most cases consisting of a negative feedback system.

IMPORTANT DEFINITIONS (Continued)

OUTPUT OFFSET VOLTAGE—The no-signal voltage produced at the output of a differential amplifier as a result of mismatch between the elements of the amplifier.

SAMPLE AND HOLD CIRCUIT—An analog storage device. An externally controlled switch applies the input signal to a low leakage capacitor during the sampling interval. At the end of this interval the switch disconnects the input signal, and the capacitor "holds" the charge that existed at the end of the sample time.

SCALING ADDER—A summing amplifier in which the input signals are "weighted" by applying them through unequal input resistors.

SLEW RATE—The maximum rate at which the output of an operational amplifier can change to follow an input change, expressed in volts per microsecond.

SUMMING AMPLIFIER—An operational amplifier in which two or more input signals are applied to the inverting input. The amplifier effectively adds these signals to produce an output (inverted) equal to their sum.

VOLTAGE FOLLOWER—An operational amplifier in which the entire output is fed back to the inverting input, resulting in a gain of 1, or unity.

ZERO CROSSING DETECTOR—A circuit that develops a pulse each time the input signal passes through zero.

ESSENTIAL SYMBOLS AND EQUATIONS

$$A_C = \frac{R_1 + R_2}{R_1} \text{ or } 1 + \frac{R_2}{R_1} \qquad (1)$$

$$A_C = -\frac{R_2}{R_1} \qquad (2)$$

$$E_O = -\left[\left(\frac{R_3}{R_1}\right) E_1 + \left(\frac{R_3}{R_2}\right) E_2\right] \qquad (3)$$

$$E_O = \frac{R_3}{R_1} (E_2 - E_1) \qquad (3a)$$

PRACTICE EXERCISE SOLUTIONS

1. In an analog circuit, the electrical action is "continuous" so that the electrical signals vary in proportion to the quantities they represent. In a digital circuit, the electrical signals switch on and off to represent the desired quantities.
2. Economy, reliability and close matching of component characteristics.
3. False—Large values of resistance and capacitance are difficult to produce, and practical inductance values are almost nonexistent in monolithic IC's.
4. The cost of additional diodes and transistors is negligible.
5. True
6. (b) ratios of values.
7. True
8. This terminal permits injection of an external control signal to control the gain of the amplifier.
9. (b) zero.
10. True
11. R_E tends to keep the total emitter current constant.
12. (b) decrease.
13. common mode rejection
14. Offset.
15. False—It is called input bias current.
16. (a) high.
17. 8
18. These resistors produce degeneration which reduces the maximum gain of the circuit but provides more uniform gain over the operating frequency range.
19. False—An emitter follower is characterized by a high input impedance and low output impedance.
20. Q_1; Q_2

PRACTICE EXERCISE SOLUTIONS (Continued)

21. (b) minimum.

22. Q_1 serves as a constant current source.

23. An operational amplifier is basically a high gain, direct-coupled amplifier.

24. (b) negative feedback from the output to the input.

25. (b) inverted.

26. False—Feedback is not used in the open-loop configuration.

27. (b) 1.

28. True

29. −10.—The gain of an inverting op amp is equal to the ratio of feedback resistance (R_2) to input resistance (R_1). The minus sign indicates the inversion produced by this configuration.

30. The value of the input resistor (R_1 in Figure 22D).

31. True

32. compensating networks

33. (a) high.

34. (b) low.

35. True

36. The level translator compensates for shifts in operating points due to the direct coupling between amplifier stages.

37. True

38. The greater the degree of compensation, the more limited the output voltage swing if the frequency is beyond the 3-dB down point.

39. (a) higher input impedance.

40. True

41. The voltage follower has a higher input impedance.

42. False—The gain of a voltage follower is 1.

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4141 BELMONT AVENUE, CHICAGO, ILLINOIS 60641

ONE OF THE
BELL & HOWELL SCHOOLS

7405A
EXAMINATION CHECK SHEET

1. A - LINEAR INTEGRATED CIRCUITS ARE SOMETIMES REFERRED TO AS -- ANALOG CIRCUITS.
Linear integrated circuits are used to produce or process electrical signals which vary in proportion to some quantity and may therefore be referred to as analog devices.

2. C - TWO COMPONENTS THAT ARE DIFFICULT TO CONSTRUCT IN INTEGRATED CIRCUIT FORM ARE -- INDUCTORS AND TRANSFORMERS.
Discrete inductors or transformers are normally used in conjunction with integrated circuits.

3. D - THE DIFFERENCE IN INPUT VOLTAGES REQUIRED TO PRODUCE EQUAL COLLECTOR VOLTAGES IN THE CIRCUIT SHOWN IN FIGURE 5 IS REFERRED TO AS THE -- INPUT OFFSET VOLTAGE.
The input offset voltage is an important parameter which can be used to evaluate the operation of the differential amplifier shown in Figure 5 or any other differential amplifier circuit.

4. C - AN IDEAL OPERATIONAL AMPLIFIER SHOULD HAVE -- AN INFINITE INPUT IMPEDANCE AND A ZERO OUTPUT IMPEDANCE.
A practical operational amplifier will have an extremely high (but not infinite) input impedance and an extremely low (but not zero) output impedance.

5. B - THE CIRCUIT SHOWN IN FIGURE 22B HAS -- A GAIN OF APPROXIMATELY ONE, OR UNITY.
This circuit is a voltage follower; therefore, the output voltage follows the input voltage applied.

6. D - THE CIRCUIT SHOWN IN FIGURE 22C WILL PRODUCE AN OUTPUT SIGNAL THAT IS -- IN PHASE WITH THE INPUT SIGNAL.
The noninverting operational amplifier circuit shown in this figure produces no phase shift but it can provide a high degree of amplification.

7. D - THE VOLTAGE GAIN OF THE CIRCUIT SHOWN IN FIGURE 22D IS DETERMINED BY THE -- RATIO OF R_2 TO R_1.
It is the ratio of R_2 to R_1, not their specific values, that determines the gain of the inverting amplifier circuit shown.

8. D - THE CIRCUIT SHOWN IN FIGURE 41 -- EFFECTIVELY ADDS THE TWO INPUT SIGNALS AND PRODUCES A SINGLE OUTPUT SUM.
The circuit is commonly referred to as a summing amplifier.

9. A - AN OPERATIONAL AMPLIFIER COMPARATOR CIRCUIT IS USED TO -- COMPARE A REFERENCE VOLTAGE WITH AN INPUT VOLTAGE.
The output of the comparator circuit varies between $+V_{CC}$, $-V_{CC}$ and zero to indicate when the input voltage is greater than, less than or equal to the reference voltage.

10. D - THE AMPLITUDE OF THE TRIANGULAR WAVEFORM PRODUCED BY THE INTEGRATOR CIRCUIT SHOWN IN FIGURE 44 CAN BE EFFECTIVELY CONTROLLED BY -- CHANGING THE VALUE OF THE CAPACITOR.
By changing the value of the capacitor, the time constant of the circuit can be made longer or shorter with respect to the period of the input squarewave signal.

QUESTIONS

IMPORTANT—These instructions **MUST** be accurately followed to avoid loss, or errors in grading.

Indicate your answer on this sheet by filling in the box for the most correct answer to each question, as illustrated in the example below.

When all questions have been answered, place the answer card in the proper position to line up the boxes on the card with the boxes on the sheet.

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LESSON CODE
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Example: A philodendron is a type of
A ☐ B ☐ C ☐ D ■
(A) tropical fish. (B) tropical bird. (C) arctic marsupial. (D) tropical plant.

1. A ☒ B ☐ C ☐ D ☐
Linear integrated circuits are sometimes referred to as
(A) analog circuits. (B) switching circuits. (C) digital circuits. (D) modulator circuits.

2. A ☐ B ☐ C ☒ D ☐
Two components that are difficult to construct in integrated circuit form are
(A) transistors and low-value resistors. (B) resistors and capacitors with low values. (C) inductors and transformers. (D) transistors and low-value capacitors.

3. A ☐ B ☐ C ☐ D ☒
The difference in input voltages required to produce equal collector voltages in the circuit shown in Figure 5 is referred to as the
(A) input bias voltage. (B) output offset voltage. (C) input offset drift. (D) input offset voltage.

4. A ☐ B ☐ C ☒ D ☐
An ideal operational amplifier should have
(A) a gain of one or unity. (B) a zero input impedance and an infinite output impedance. (C) an infinite input impedance and a zero output impedance. (D) a zero common mode rejection ratio.

5. A ☐ B ☒ C ☐ D ☐
The circuit shown in Figure 22B has
(A) an extremely high gain. (B) a gain of approximately one, or unity. (C) an extremely low input impedance. (D) an extremely high output impedance.

6. A ☐ B ☐ C ☐ D ☒
The circuit shown in Figure 22C will produce an output signal that is
(A) 180° out-of-phase with the input voltage. (B) 90° out-of-phase with the input voltage. (C) always smaller than the input signal. (D) in phase with the input signal.

7. A ☐ B ☐ C ☐ D ☒
The voltage gain of the circuit shown in Figure 22D is determined by the
(A) open-loop gain of the integrated circuit. (B) value of R_2 only. (C) value of R_1 only. (D) ratio of R_2 to R_1.

8. A ☐ B ☐ C ☐ D ☒
The circuit shown in Figure 41
(A) has a voltage gain that is determined by the ratio of R_3 to R_4. (B) has a voltage gain that is determined by the ratio of R_1 to R_2. (C) effectively determines the difference between the two input signals. (D) effectively adds the two input signals and produces a single output sum.

9. A ☒ B ☐ C ☐ D ☐
An operational amplifier comparator circuit is used to
(A) compare a reference voltage with an input voltage. (B) add a reference voltage to an input voltage. (C) compare two input voltages and produce an output voltage that is equal to their sum. (D) compare two reference voltages and produce an output voltage that is equal to their sum.

10. A ☐ B ☐ C ☐ D ☒
The amplitude of the triangular waveform produced by the integrator circuit shown in Figure 44 can be effectively controlled by
(A) changing the value of the 9.1 kΩ resistor. (B) changing the value of the 100 kΩ resistor. (C) using an amplifier with a higher open-loop gain. (D) changing the value of the capacitor.

PRACTICE EXERCISE SOLUTIONS (Continued)

43. The sinewave component will have a smaller amplitude.—In an inverting configuration, the gain is equal to the feedback resistance divided by the input resistance.

44. (a) an integrator.

45. This resistor limits high-frequency gain so that noise pulses at the input do not receive excessive amplification.

46. gyrator

47. True

48. The output of the operational amplifier is the negative saturation voltage (the maximum negative voltage swing) of the op amp.

49. This diode limits the positive output swing to +3.5 volts, and the negative output swing to −0.7 volt.

50. False—Slew rate decreases as the degree of compensation increases. For comparator applications, an uncompensated amplifier is preferred.

51. (b) a voltage follower.

QUESTIONS

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The circuit shown in Figure 22B has
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REGULATED POWER SUPPLIES

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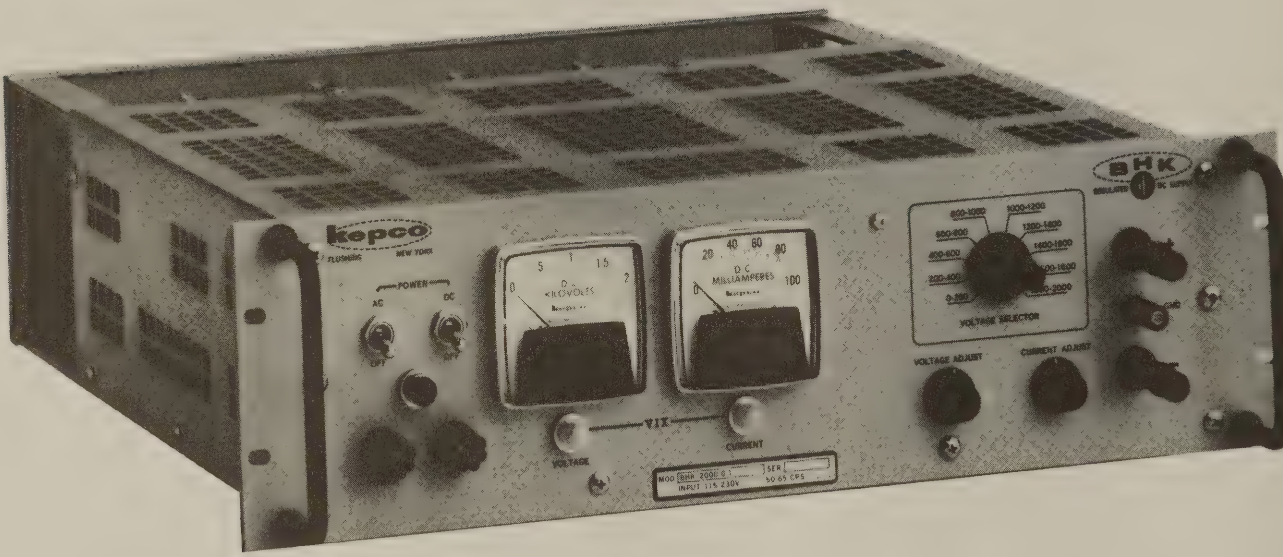

This laboratory automatic crossover power supply is designed for rack-mounted operation. It features metered voltage and current adjustments of 0-2000 volts and 0-100 mA. Monitor lamps indicate whether the supply is in voltage or current regulating modes.

Courtesy Kepco, Inc.

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> *The world hates change, yet it*
> *is the only thing that has brought*
> *progress.*
> *—Charles F. Kettering*

REGULATED POWER SUPPLIES

Most electronic equipment requires operating voltages which must remain essentially constant. The output of an ordinary power supply varies with changes in input voltage or changes in load conditions. A supply of this type is not suitable for applications where operating voltages and currents must remain constant. For constant voltage or constant current applications, regulated power supplies are used.

A regulated power supply has added regulator circuits that prevent changes in output that might otherwise occur. Most regulated supplies start with output voltages that are higher than needed, and then reduce the outputs to the desired values. The amount of reduction may be varied to compensate for other changes.

The output voltage of the basic (unregulated) power supply depends on the ac line voltage applied to its input. When the ac line voltage increases, the high voltage applied to the rectifier increases the direct voltage produced at the output terminals. When the ac line voltage decreases, the direct voltage output is reduced. Variations in load current will also cause the output voltage of the supply to vary. An undesired quantity that affects the output is the alternating voltage component that passes through the filter and causes a steady pulsation in the direct voltage output. The alternating component is known as ripple voltage, and causes improper operation of any electronic instruments that require an unvarying supply voltage.

THE BASIC POWER SUPPLY

Figure 1 is the schematic diagram of a type of power supply in common use today. This circuit employs a power transformer, a full wave rectifier, and a capacitor input, pi-type filter. The secondary winding of the power transformer is center tapped and the ac voltages across sections A and B are equal. This causes silicon diodes D_1 and D_2 to conduct equally on alternate half cycles of the input voltage.

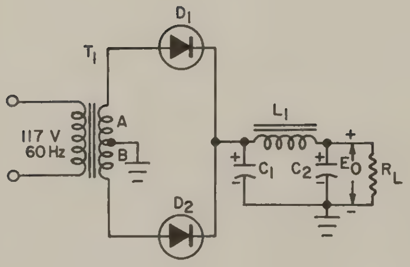


Figure 1

The amplitude of the dc output voltage, E_O, depends mainly on the design of transformer T_1. If we assume that the voltage across each section of the secondary is 10 volts (rms), the theoretical maximum value of E_O is 10 × 1.4 = 14 volts dc.

A power supply is normally designed to supply a certain load current at its rated output voltage. If the load current is relatively constant, the output voltage stays reasonably constant, and a basic power supply like that of Figure 1 would be suitable.

In most electronic equipment, the load conditions change considerably during operation. When this happens, the output of the supply, E_0, also changes slightly. In general, when load current increases, E_0 decreases, and when load current decreases, E_0 increases. The amount of change in E_0 caused by a given change in load current is called regulation, or more specifically, load regulation.

The output voltage may also change if the input ac voltage changes. In general, if the input voltage does affect the output, when the input voltage increases, E_0 increases, and when the input voltage decreases, E_0 decreases. To distinguish it from load regulation, this change in E_0 due to an ac input change is called line regulation.

Both of these types of regulation are important in selecting and using power supplies. Wide changes in supply voltage could prevent the load equipment from operating, and in certain situations, might even lead to destruction of the equipment.

VOLTAGE REGULATION

The voltage regulation of a power supply determines how much change in output voltage occurs when a given change in load current, line voltage, or some other controlling factor occurs. Because load regulation is the most common form of regulation, let's examine it first.

The amount of load regulation is determined by comparing the change in E_0 that occurs in going from an unloaded condition to a fully loaded condition. This change is expressed as a percentage, by Equation 1.

$$\% \text{ Reg} = \frac{E_{\text{NO LOAD}} - E_{\text{FULL LOAD}}}{E_{\text{FULL LOAD}}} \times 100 \qquad (1)$$

In a perfect power supply, the output voltage would remain constant regardless of any change in load current. For example, if E_0 in Figure 1 is 14 volts under no-load conditions, and remains 14 volts when the supply is providing full-load current, the percentage of regulation is:

$$\% \text{ Reg} = \frac{E_{\text{NO LOAD}} - E_{\text{FULL LOAD}}}{E_{\text{FULL LOAD}}} \times 100$$

$$= \frac{14 - 14}{14} \times 100 = 0\%.$$

We see, then, that perfect regulation is 0%. For comparison, suppose that the output voltage drops from 14 volts to 10 volts when full load is applied. The regulation is, using Equation 1:

$$\% \text{ Reg} = \frac{E_{\text{NO LOAD}} - E_{\text{FULL LOAD}}}{E_{\text{FULL LOAD}}} \times 100$$

$$= \frac{14 - 10}{10} \times 100 = 40\%.$$

Perfect regulation is impossible to achieve, but a good power supply is designed to have as low a percentage of regulation as possible.

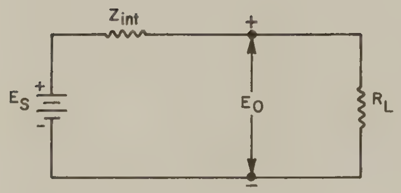


Figure 2

Some of the factors which can affect regulation of the power supply in Figure 1 are the resistance of the T_1 and L_1 windings, the core losses of T_1 (flux leakage, eddy current losses, hysteresis loss), and the forward conduction resistance of D_1 and D_2. To simplify the analysis of the power supply, the circuit of Figure 1 can be shown as in Figure 2. In this practical example, we will consider the condition of minimum load current being drawn to be equivalent to the no-load condition. Here, the no-load output voltage is E_S, while all of the loss factors are lumped into the internal impedance, Z_{int}. These factors, with the load resistance value, determine the load current, I_L.

$$I_L = \frac{E_S}{Z_{int} + R_L} \tag{2}$$

To analyze Figure 2, let's use some specific values. For example, let $E_S = 15$ volts, $Z_{int} = 100\Omega$ and $R_L = 1.4\ \text{k}\Omega$. In this case, the load current is:

$$I_L = \frac{E_S}{Z_{int} + R_L} = \frac{15}{100 + 1.4\text{K}} = \frac{15}{1.5\text{K}} = 10 \text{ mA}.$$

With 10 mA of load current, the voltage lost across Z_{int} is 1 volt and E_O is 14 volts. The regulation is:

$$\% \text{ Reg} = \frac{E_{\text{NO LOAD}} - E_{\text{FULL LOAD}}}{E_{\text{FULL LOAD}}} \times 100$$

$$= \frac{15 - 14}{14} = 100 = 7.14\%.$$

If this same power supply is connected to a load resistance of 400Ω, the load current is:

$$I_L = \frac{E_S}{Z_{int} + R_L} = \frac{15}{100 + 400} \times \frac{15}{.5\text{K}} = 30 \text{ mA}.$$

With 30 mA of load current, the voltage lost across Z_{int} is 3 volts and E_O is 12 volts. The regulation is:

$$\% \text{ Reg} = \frac{E_{\text{NO LOAD}} - E_{\text{FULL LOAD}}}{E_{\text{FULL LOAD}}} \times 100$$

$$= \frac{15 - 12}{12} \times 100 = 25\%.$$

We see, then, that another important specification of a power supply is the maximum load current that it is designed to supply. For the power supply just analyzed, if the maximum load current is specified as 10 mA, the % of Regulation can be specified as 7.14%. However, if the maximum load current is specified as 30 mA, the % of Regulation must be specified as 25%.

To improve the voltage regulation of a power supply, the designer keeps the internal impedance as low as is practical. This is accomplished by using a high-quality power transformer and filter choke and by using low-loss rectifiers, such as silicon diodes. In certain applications however, even the use of quality components does not improve the regulation enough and additional circuitry must be used to improve the regulation further.

One simple way to improve power supply regulation is by connecting a bleeder resistor, R_B, as shown in Figure 3. This bleeder resistor is a permanent part of the power supply and remains connected at all times. To analyze the effect of the bleeder resistor, let's assume that $E_S = 15$ volts, $Z_{int} = 100\Omega$ and $R_B = 400\Omega$. With no load connected, the sum of Z_{int} and R_B allows a bleeder current, I_B, of 30 mA. The voltage lost across Z_{int} is 3 volts, and the no-load E_O is 12 volts.

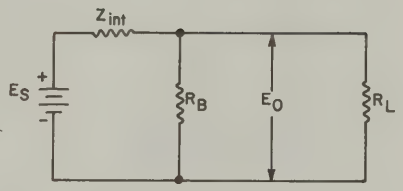


Figure 3

When a load resistance of 1.4K ohms is connected across the power supply output terminals, the parallel resistance of R_L and R_B is about 311 ohms. Added to the 100 ohms of Z_{int}, the total impedance across the power supply is 411 ohms, the current through Z_{int} is about 36 mA, the voltage lost across Z_{int} is about 3.6 volts, and E_O decreases to 11.4 volts. The regulation now is

$$\% \text{ Reg} \times \frac{E_{\text{NO LOAD}} - E_{\text{FULL LOAD}}}{E_{\text{FULL LOAD}}} \times 100$$

$$= \frac{12 - 11.4}{11.4} \times 100 = 5.26\%.$$

We see, then, that adding R_B to the power supply improves the regulation from 7.14% to 5.26%. A further improvement can be effected by making R_B smaller so that the bleeder current, I_B, becomes larger. In fact, the greater the ratio of bleeder current to load current, the better the power supply regulation.

An obvious fault of the bleeder resistor is its "wasted" power dissipation, which degrades the efficiency of the supply. To provide a noticeable improvement in regulation, the bleeder current must be large, but because this current is bypassed around the load, it is lost as far as the load is concerned. Also, the bleeder has little, if any, effect on line regulation, which may be an important factor in some equipment. In general, the bleeder resistor is an effective regulating device only in low-power systems, operating from stable ac sources where close regulation is not required.

VOLTAGE REGULATORS

To meet the demands of modern electronic equipment where changes of a fraction of a volt may completely upset circuit operation, special voltage regulator circuits must be added to the power supply. These circuits sense any attempted change in output voltage and counteract the change, holding the output essentially constant. So effective are these regulators that power supplies with regulation percentages of less than 1% are common.

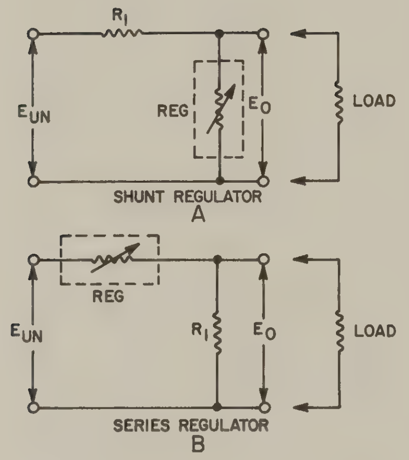


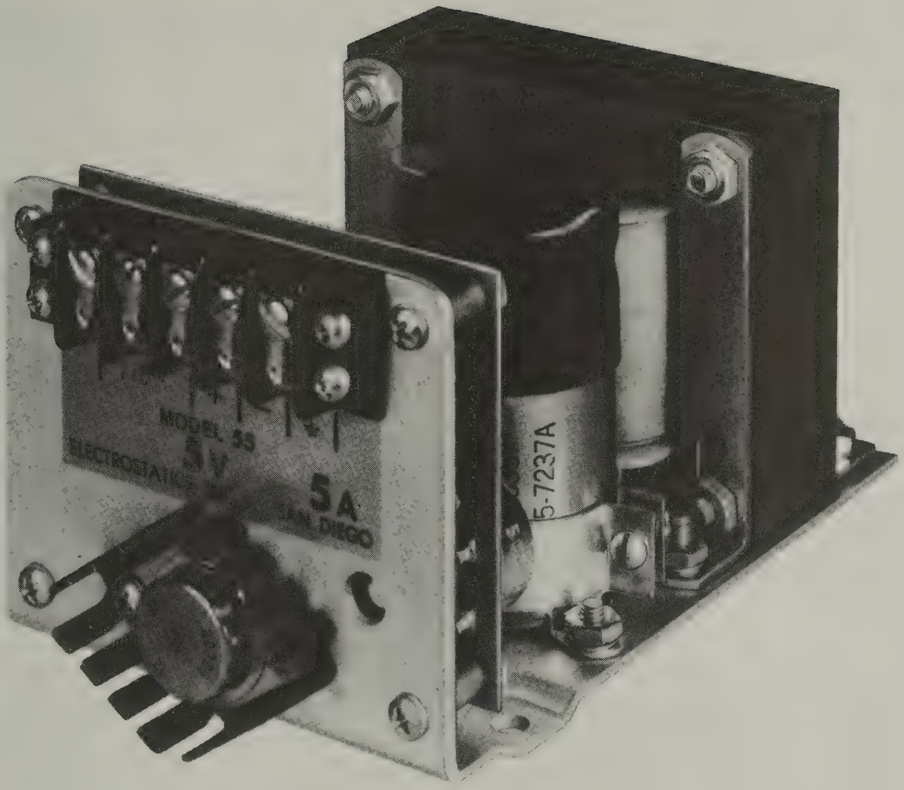
Figure 4

Voltage regulators are classed as shunt or series regulators, depending on the position of the regulating element with respect to the load. These two classes of regulators are illustrated by the simplified diagrams of Figure 4. In each circuit, the unregulated output, E_{UN}, of a power supply is applied to the regulating element and resistor R_1 in series. The element between the unregulated supply and the output terminal must "pass" the load current, and is therefore called the pass element. In Figure 4A, R_1 is the pass element. In Figure 4B, the regulator is the pass element. In either circuit, *output voltage E_O is the difference between E_{UN} and the voltage drop across the pass element.*

Figure 4A is the basic shunt regulator circuit. In this circuit, the regulating element is in shunt (parallel) with the load. The regulating element is shown as a variable resistance. Its function is to vary its resistance to compensate for any changes in either load conditions or input voltage so that E_O remains constant.

In Figure 4A, E_O is the difference between E_{UN} and the voltage drop across pass element resistor R_1. To provide *load regulation,* the regulating element must maintain a constant current through R_1 so that the voltage across R_1 remains constant. For example, if load current increases by 1 mA, the regulator current must decrease by the same amount (1 mA) to maintain the net current through R_1 constant.

To provide *line regulation* in this circuit, the regulating element must vary the current through R_1 so that the voltage across R_1 varies by the same



This compact power supply is designed for use with integrated circuits. It provides 5 volts output at 5 amperes maximum load current with a load regulation of 0.05% and line regulation of 0.005%.

Courtesy Electrostatics, Inc.

amount as any change in E_{UN}. For example, if E_{UN} increases by 1 volt, the regulating element must increase the current through R_1 so that the voltage across R_1 also increases by 1 volt. The increase in E_{UN} is "absorbed" by R_1 and does not appear at the output.

In the series regulator of Figure 4B, E_{UN} again divides between the regulating element and R_1. But, in this instance, output voltage E_O is the difference between E_{UN} and the voltage drop across the regulating element itself. In this circuit, the load current passes through the regulating element, which means that the voltage across this element is proportional to the load current. If the load current increases, the resistance of the regulating element must decrease so that the voltage across it remains constant. With E_{UN} constant, and the drop across the regulating element constant, E_O must also remain constant.

If E_{UN} increases, the regulating element of Figure 4B must increase its resistance just enough to hold the current constant. With an increase in input voltage, and a constant current, the voltage drop across the regulating element increases by the same amount as the increase of input voltage. The output, E_O, is therefore unchanged.

The circuits of Figure 4 illustrate the basic principles of voltage regulation. We will now consider these circuits in more detail to see how they are implemented in practice.

Shunt Voltage Regulator

Earlier, the basic shunt regulator was described as a variable resistance in parallel with the load. In discussing Figure 4A, we observed that the regulating element must somehow change its resistance to compensate for changes in load current or supply voltage. A semiconductor that has this ability, ~~and is widely used for just this~~ purpose, is the zener diode.

The basic operation of the zener diode was discussed in an earlier lesson. However, we will again examine the special features of this device which make it a valuable regulating element. You learned earlier that the zener diode is capable of conducting a certain amount of reverse current when a certain reverse voltage is applied between its anode and cathode. When operating in an area called its zener region, it can produce large changes in reverse current in response to small changes in reverse voltage. Looking at it another way, large changes in reverse current produce very little change in reverse voltage.

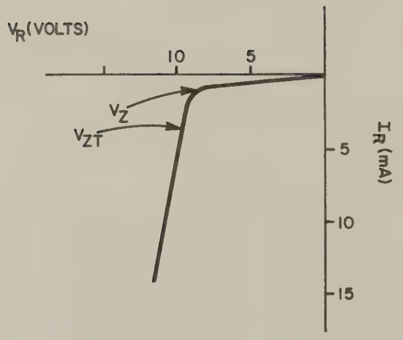


Figure 5

The curve of Figure 5 shows the reverse conduction characteristic of a particular type of zener diode. The value of the voltage that causes the sudden increase of reverse current, called the zener voltage, V_Z, is about 9.9 volts. When measuring the characteristics of a zener diode, the manufacturer increases the reverse voltage slightly beyond V_Z to obtain a specified amount of reverse current. In Figure 5, the reverse voltage is increased to obtain 5 mA of reverse current. The value of this voltage (10 volts) is then specified as the zener test voltage, and is labeled V_{ZT} in Figure 5. Many other types of zener diodes are manufactured with a wide range of reverse voltage ratings and reverse current ratings to suit almost any requirement.

Now we will see how the zener diode can be used to provide voltage regulation. Figure 6 shows a zener diode connected as a shunt regulator. The diode is reverse biased by E_{UN}, the unregulated output of a power supply. To analyze the circuit action we will assume typical circuit values and see how the circuit responds to changes in load current or input voltage.

The following Practice Exercise questions cover the subjects which you have just studied. They are:

THE BASIC POWER SUPPLY

VOLTAGE REGULATION

VOLTAGE REGULATORS

1. The power supply of Figure 1 is usually satisfactory when the (a) load resistance varies a great deal, (b) load current varies a great deal, (c) load resistance and load current are fairly constant.

2. A power supply with 5% regulation is better than one with 10% regulation. True or False?

3. The no-load output voltage of a power supply is 24 volts while the full-load output voltage is 20 volts. What is the % of Regulation?

4. What components determine the internal impedance of a power supply?

5. The power supply shown in Figure 1 will most likely provide a (a) higher output voltage if the ac input voltage increases, (b) lower output voltage if the ac input voltage increases.

6. In Figure 3, the regulation of the power supply is improved when (a) the resistance of R_B is decreased, (b) the resistance of R_B is increased, (c) the resistance of Z_{int} is increased.

7. Maintaining a constant output voltage even during changes in ac input voltage is called (a) line regulation, (b) load regulation.

8. What are the two basic classes of voltage regulators?

9. In a voltage regulator, the element that carries the load current is called the __________ element.

10. If the load current increases in the shunt regulator of Figure 4A, the current through the regulating element must (a) increase, (b) decrease, (c) remain the same to prevent a change in E_O.

11. If E_{UN} decreases in the series regulator of Figure 4B, the voltage drop across the regulating element must ______________ to hold E_O constant.

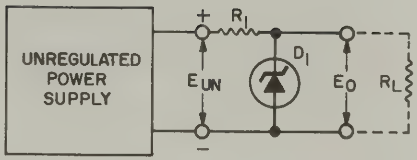


Figure 6

We will assume that the unregulated input voltage, E_{UN}, of Figure 6 is variable from 25 to 30 volts and it is desired to obtain a regulated voltage, E_O, of 10 volts. We will also assume that zener diode D_1 has the characteristics shown in Figure 5, and that R_1 is a 1K ohm resistor.

With no load (R_L disconnected), the reverse current of D_1 is 15 mA. This causes the voltage across R_1 to be 15 volts, E_{UN} to be 25 volts, and E_O to be 10.2 volts. Now, if a load, R_L, of 1K ohm is connected across E_O, the load current through R_L is 10 mA, the regulated output voltage across D_1 decreases slightly to 10 volts, the reverse current through D_1 decreases to 5 mA, but the total current through R_1 remains constant at 15 mA. We see, then, that a change in load current of 10 mA causes a change in E_O of only 0.2 volt, and the regulation is:

$$\% \text{ Reg} = \frac{E_{\text{NO LOAD}} - E_{\text{FULL LOAD}}}{E_{\text{FULL LOAD}}} \times 100$$

$$= \frac{10.2 - 10}{10} \times 100 = 2\%.$$

In addition to compensating for changes in load current, the zener diode also compensates for changes in the unregulated voltage, E_{UN}. For example, assume that the circuit of Figure 6 is operating normally with a load resistance of 1K ohm, E_O of 10 volts and E_{UN} of 25 volts. Assume further that an increase in the line voltage to the unregulated power supply causes E_{UN} to increase from 25 volts to 30 volts. In this case, the reverse zener current increases from 5 mA to 10 mA, causing the voltage across R_1 to increase from 15 volts to 20 volts. As a result, the regulated output voltage, E_O, remains at 10 volts.

As good as a zener diode appears to be, there are limits to its capabilities which must not be exceeded. A zener diode having the characteristics of Figure 5 must not be used in a circuit where the reverse current will exceed 15 mA. This particular zener diode is designed to provide 15 mA or less of shunt current, and a reverse current in excess of 15 mA will cause the diode to overheat, resulting in its destruction. Other zener diodes are available that have increased reverse current capability.

In general a shunt regulator offers relative simplicity which results in economies of cost and physical size. However, the regulating element draws a "bleeder" current from the supply, causing a power loss that lowers the supply's efficiency. Also, the output voltage is restricted to a fixed value determined by the voltage characteristics of the zener diode used. This type of regulator is commonly used in low-power applications where a fixed, stable dc voltage is required. Examples of this are a bias stabilizer for transistor circuits or a stable reference voltage for more elaborate regulators.

Series Voltage Regulator

The series regulator system illustrated in Figure 4B is the overwhelming choice of power supply designers for modern electronic equipment. Taking advantage of advances in semiconductor technology, designers have expanded the simple principle of series regulation to provide power supplies with stable outputs in operating voltage ranges from a fraction of a volt well into the kilovolt regions.

In a series regulator, the output voltage is compared to a reference voltage and any variation in output is used to control the conduction of the pass element. This idea is demonstrated in simple form by the circuit of Figure 7. In this circuit, transistor Q_1 is the pass element, and zener diode D_1 provides the reference voltage. Output voltage E_O is compared to the reference voltage to control the conduction of Q_1.

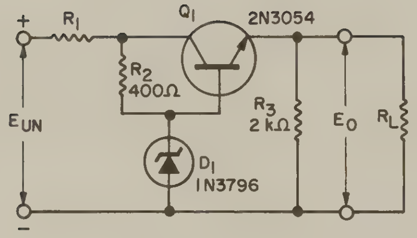


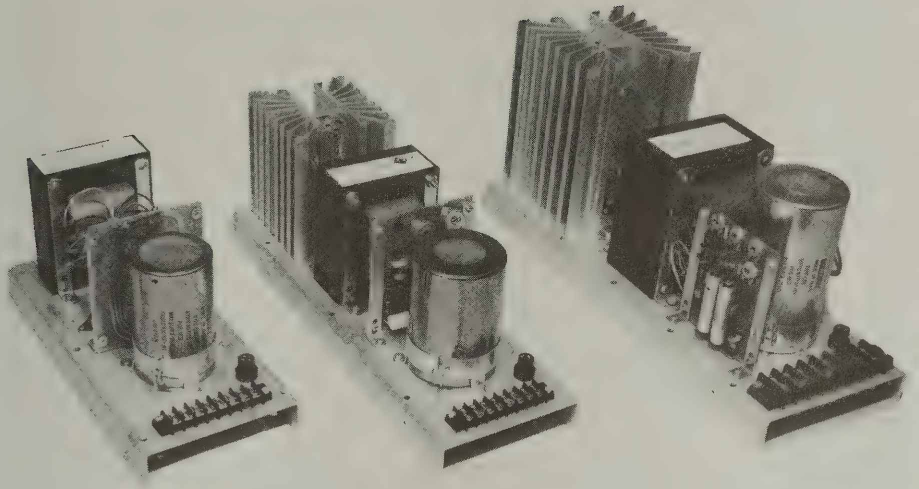
Figure 7

The basic operation of the Figure 7 circuitry is straightforward. The regulated output voltage, E_O, is equal to the voltage across the zener diode, D_1, minus the base-to-emitter voltage of the pass transistor, Q_1. Any attempted change in the regulated output voltage, E_O, causes a change in the Q_1 base-to-emitter bias that causes the Q_1 conduction to change by the proper amount to hold E_O almost constant.

To illustrate the circuit's action, let's assume that the unregulated voltage, E_{UN}, is 35 volts, the zener diode voltage is 20.7 volts, the Q_1 base-to-emitter voltage is 0.7 volt, the Q_1 collector-to-emitter voltage is 15 volts, and E_O is 20 volts. Now, let's assume that E_{UN} decreases to 30 volts. Because of this, E_O will attempt to decrease also. However, as E_O decreases from 20 volts to 19.9 volts, the Q_1 base-to-emitter voltage increases to 0.8 volt, the conduction of Q_1 increases, and the Q_1 collector-to-emitter voltage decreases to 10.1 volts, holding E_O at 19.9 volts. We see that a change of 5 volts in E_{UN} caused a change of only 0.1 volt in E_O.

Like any other circuit, the regulator of Figure 7 has its limitations. This circuit has been selected to supply a load current of 0.5A at an E_O of 20 volts with a Q_1 base current of about 10 mA. To obtain stable operation, the current through the zener diode, D_1, should be several times larger than the Q_1 base current. Therefore, D_1 is selected because its zener voltage is 20.7 volts with 30 mA of current through it. Since the zener diode current and the Q_1 base current are through R_2, the total current through R_2 is about 40 mA and the voltage across R_2 is about 14 volts.

Since the regulator is designed to supply a maximum load current of 0.5A at an E_O of 20 volts, the load resistance, R_L, should not be less than 40 ohms.



A series of regulated power supplies designed for use with various semiconductor circuits is shown. Line and load regulation are both within 0.25%. Multiple pass transistors are used to provide safe operation at powers up to 120 watts.
Courtesy Tele-Dynamics Wanlass
Division of AMBAC

Resistor R_1 is merely a current limiting resistance added to the circuit in the event the output terminals accidentally become shorted. During normal operation, R_1 has very little effect on the circuit and could be omitted. R_3 is used to prevent E_O from rising to an excessive value if R_L is removed. The current through R_3 during normal operation is small enough to be disregarded.

Previously, we mentioned that good voltage regulation is obtained when the internal impedance of the power supply is very low. For the supply of Figure 7, a 500 mA change in load current (from no load to full load) causes E_O to change about 0.8 volt. The internal impedance of this supply can be determined by using the following equation:

$$Z_{int} = \frac{\Delta E_O}{\Delta I_L}$$

This equation simply states that the internal impedance (Z_{int}) is equal to the change in output voltage (ΔE_O) divided by the change in load current (ΔI_L). By substituting actual values into this equation we get:

$$Z_{int} = \frac{.8}{.5} = 1.6 \text{ ohms.}$$

The power supply therefore effectively has an internal impedance of 1.6 ohms.

The regulation of the supply can also be determined as follows:

$$\% \text{ Reg} = \frac{E_{\text{NO LOAD}} - E_{\text{FULL LOAD}}}{E_{\text{FULL LOAD}}} \times 100$$

$$= \frac{20.8 - 20}{20} \times 100 = 4\%.$$

For some applications, the regulator of Figure 7 is quite satisfactory. However, if lower internal impedance and better regulation are required, it is necessary to add an amplifier to the circuit.

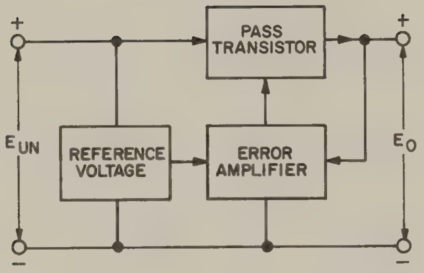


Figure 8

The block diagram in Figure 8 shows how the amplifier is added to a series regulator. A sample of the output voltage, E_O, and a constant reference voltage are applied to an error amplifier. Any change in E_O is amplified and used to control the conduction of the pass transistor which, in turn, holds E_O nearly constant.

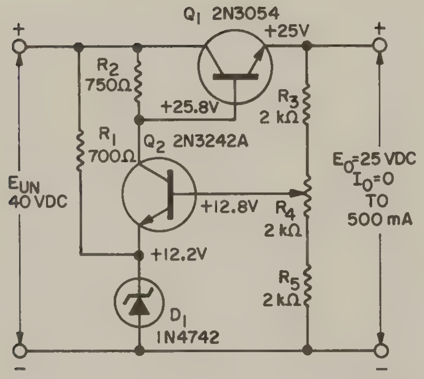


Figure 9

The schematic diagram of a series regulator which utilizes an error amplifier is shown in Figure 9. Any change in E_O, caused by a change in load current or a change in E_{UN}, is applied through R_4 to the base of Q_2. The amplified error signal appears at the Q_2 collector and Q_1 base, where it controls the conduction of Q_1 to hold E_O nearly constant. Potentiometer R_4 is used to adjust E_O to any specified voltage from 20 to 30 volts dc. Voltages shown at the transistor elements are measured with respect to the negative output terminal and are for an E_O of 25V dc.

To analyze the regulator of Figure 9, it is helpful to understand why the various components were selected. First, the amplitude of E_O and the maximum value of I_O are selected. In this example, E_O is chosen to be 25V dc and the maximum I_O is 500 mA. For any voltage regulator to function properly, the unregulated voltage must be greater than the regulated voltage. This means that a power supply like Figure 1 can be used to provide an unregulated voltage, E_{UN}, of 40V dc.

Next, a pass transistor is chosen for Q_1 that is capable of supplying 500 mA of collector current and has a fairly high forward current gain. The 2N3054 transistor provides 500 mA of collector current and has an h_{fe} (forward current gain) of 50. Therefore, the base current of Q_1 is 10 mA.

Next, the error amplifier, Q_2, must be capable of supplying a collector current that is equal to about twice the Q_1 base current, or 20 mA. The 2N3242A transistor provides this 20 mA of collector current. Because it has an h_{fe} of at least 100, it requires only 0.2 mA of base current.

Next, the zener diode, D_1, is selected to provide both the Q_2 collector current of 20 mA and twice this value (40 mA) through R_1 so that changes of Q_2 collector current will have very little effect upon the zener voltage, and the Q_2 emitter voltage will remain constant. The zener voltage can be anywhere between 10 and 15 volts and still allow a suitable operating voltage to appear across Q_2; therefore, a 1N4742 zener diode was selected. This diode provides about 12.2 volts at 60 mA (20 mA through Q_2 and 40 mA through R_1).

Determining some resistor values comes next. Since the voltage dropped across R_1 is 28 volts ($E_{R_1} = E_{UN} - E_{D_1} = 40 - 12 = 28$), and the current through it is 40 mA, R_1 is 700 ohms.

During normal operation of the regulator, it is desirable for the Q_1 base voltage to remain nearly constant. This means that changes of Q_1 base current must be accompanied by equal and opposite changes of Q_2 collector current so that the current through R_2 remains constant at about 20 mA. Since the current through R_2 is 20 mA and the voltage across R_2 is about 15 volts ($E_{R_2} = E_{UN} - E_{B_1} = 40 - 25 = 15$), R_2 is 750 ohms.

Previously, we mentioned that the Q_2 base current is about 0.2 mA. An examination of Figure 9 shows that this base current is through R_3 and R_4. To prevent changes of Q_2 base current from having any effect upon the voltage at the movable contact of R_4, the bleeder current through the voltage divider (R_3, R_4 and R_5) should be about 20 times the value of the Q_2 base current. Therefore, the bleeder current should be about 4 mA. With an E_O of 25V dc, the bleeder resistance is 6K ohms. This 6K ohms is then divided between R_3, R_4 and R_5 so that the voltage at the base of Q_2 is slightly greater than the Q_2 emitter voltage. This arrangement permits small adjustments in the Q_2 base current and insures that Q_2 is not damaged from excessive base current. The actual voltage values are shown on the schematic diagram.

Now that we have an idea of the voltages and currents in the regulator circuit, let's deliberately vary the load current and analyze the changes that occur to hold E_O nearly constant. Suppose that a load resistance of 100 ohms is connected across the regulator output terminals, so that the output current is 250 mA. Now, disconnect the load resistance so that the output current drops to zero and the only current being supplied by the regulator is the bleeder current.

When the load resistance is disconnected, the output voltage, E_O, starts to rise. This causes the voltage at the movable contact of R_4 (and at the Q_2 base) to rise. Since the Q_2 emitter voltage is held constant, the increase of Q_2 base voltage increases the Q_2 base current which, in turn, increases the Q_2 collector current. The increased Q_2 collector current increases the voltage drop across R_2 which decreases the Q_1 base-to-emitter voltage. This causes the Q_1 base current to decrease which causes the Q_1 collector current to decrease by the same amount that the load current decreased and also causes the Q_1 collector-to-emitter voltage to increase. The increased Q_1 collector-to-emitter voltage opposes the increase in E_O and forces the E_O to remain nearly constant.

In addition to controlling E_O as the load current changes, the regulator also controls E_O as the unregulated input voltage, E_{UN}, changes. The circuit action is about the same as for changes in load current. When the unregulated input voltage increases, E_O starts to increase. As a result, the following changes occur: the Q_2 base voltage increases and causes the Q_2 base current to increase. This, in turn, causes the Q_2 collector current to increase which causes the voltage across R_2 to increase. The Q_1 base voltage therefore decreases and causes the Q_1 base current to decrease, which, in turn, causes the Q_1 collector current to decrease. This means that the Q_1 collector-to-emitter voltage increases and E_O is forced to remain nearly constant.

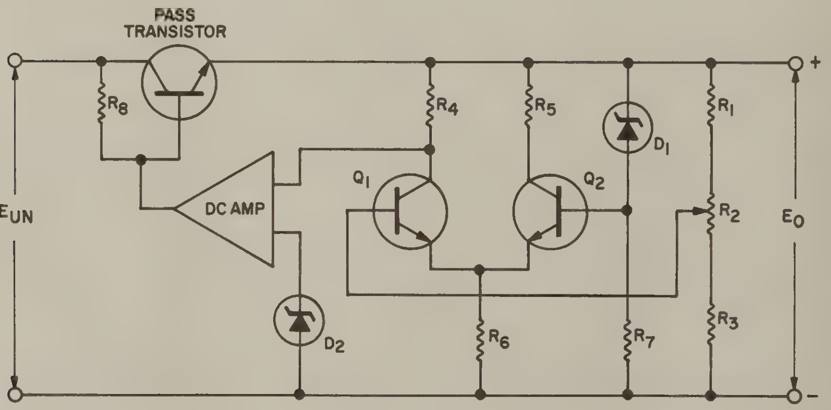


Figure 10

The regulator of Figure 9 is suitable for many applications. The error amplifier, Q_2, makes it sensitive to relatively small changes in E_O. The sensitivity can be improved further by using a differential amplifier as the error amplifier, as shown in Figure 10. Here, Q_1 and Q_2 form an emitter-coupled differential amplifier, with the base of Q_2 held at the reference potential by the reference voltage developed by D_1. The sample of E_O is applied to the base of Q_1 from the movable contact on output voltage control potentiometer R_2.

The error signal at the collector of Q_1 is fed to a conventional dc amplifier whose output drives the pass transistor. The advantage of this arrangement is the inherent high sensitivity and stability of the differential amplifier. It is often used in laboratory-type regulated supplies, where very accurate regulation is essential. It is also very common in integrated circuit regulators, which we will consider later in this lesson.

Another common method of increasing sensitivity is the use of a Darlington amplifier in the pass stage. In Figure 11, transistor Q_3 has been added to the circuit of Figure 9 to form a Darlington amplifier with Q_1. The rest of the circuitry and the overall operation of the circuit are essentially the same as in Figure 9.

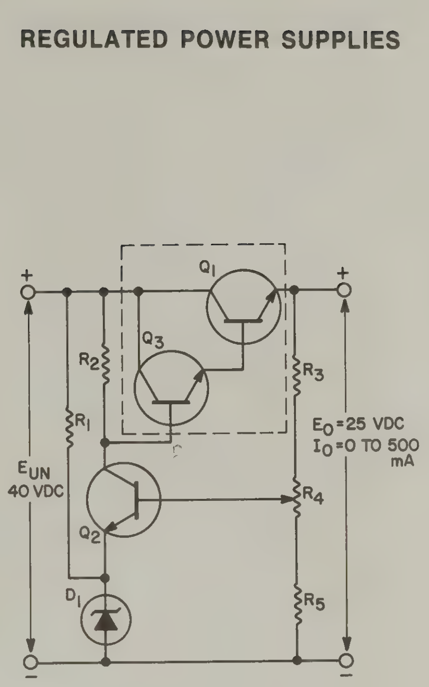


Figure 11

The advantage of the Darlington amplifier is its high current gain. This high gain is obtained because the individual gains of Q_1 and Q_3 multiply to produce the overall gain of the Darlington circuit.

The Darlington amplifier is also used to control larger amounts of load current. To supply additional load current, a higher current transistor must be used for Q_1 and the source of unregulated voltage must also be capable of supplying the additional current. The actual resistance values, the zener diode type and the transistor types are selected in the manner previously explained for Figure 9 and are dependent upon the desired values of E_0 and load current.

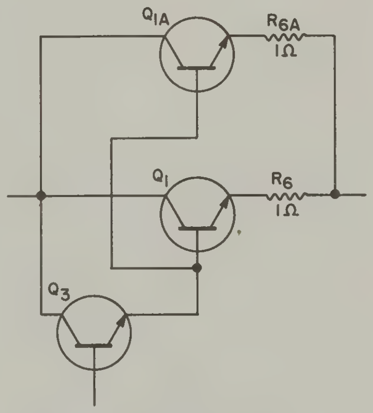
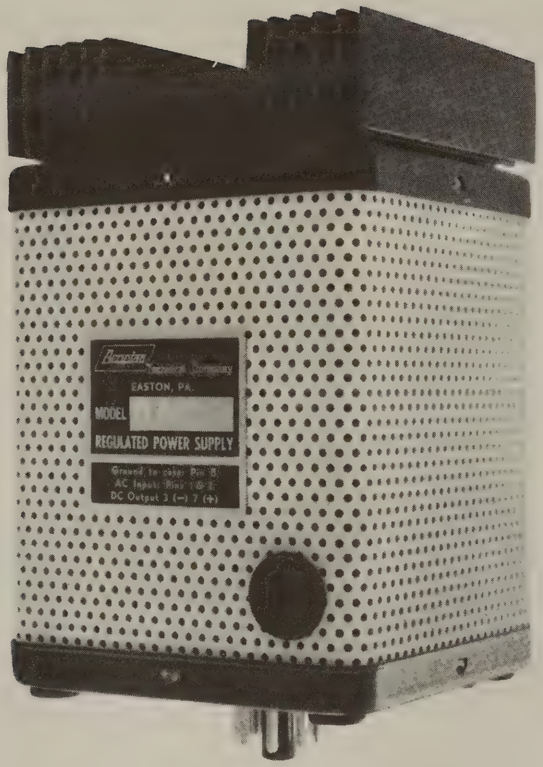


Figure 12

In commercial regulated power supplies, a variety of additional features may be found. For example, to double the current handling capability of the regulator of Figure 11, another transistor of the same type is connected in parallel with Q_1, as shown in Figure 12. To be sure that equal currents are handled by Q_1 and Q_{1A}, current sharing resistors R_6 and R_{6A} are connected into the emitter circuit. The inverse feedback caused by R_6 and R_{6A} counteracts any small difference of characteristics in the two transistors and causes their collector currents to be approximately equal.

Current handling capacity is a prime factor in most power supplies. Multiple paralleling of pass transistors can be used to satisfy the load current requirements. In fact, some regulated power supply manufacturers provide terminals on their units to permit the user to add his own pass transistors externally. The only drawback is that, for adequate power dissipation, these pass transistors must have suitable heat sinks.

The output of the series regulators previously discussed can only be adjusted over a limited range (or "slot") of voltages. However, this limited range of adjustment is satisfactory in many applications. In fact, most general purpose power supplies are constructed in this manner. In some applications however, it is important to be able to adjust the output for very low voltages or even down to zero. Adjustment to zero is an important feature in some laboratory power supplies which are used to determine the



This regulated supply is designed for plug-in mounting. Among its features are a separate referenced voltage supply to improve operating stability.
Courtesy Acopian Corporation

characteristics of various electronic components and to test the operation of a variety of circuits.

In Figure 9, the zener diode used as the reference source limits the lower voltage level of the output, since the output must at least equal the zener voltage of the diode.

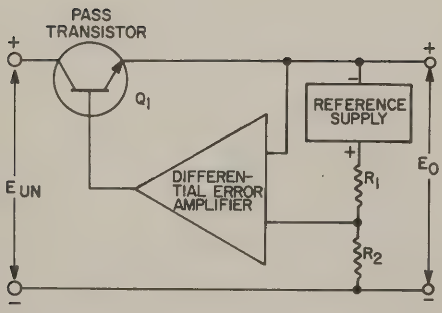


Figure 13

To overcome this limitation, the reference voltage is often obtained from a separate power supply, as shown in Figure 13. The error amplifier used in the circuit is a differential amplifier similar to the one shown in Figure 10. The circuit functions as follows. The reference supply causes a small current through resistors R_1 and R_2, and the voltage developed at the junction of these two resistors provides one input to the error amplifier. The other input to the error amplifier is obtained from the positive side of the regulated power supply. The error amplifier compares these two input voltages to produce an error signal that controls the conduction of the pass transistor, Q_1. When the reference supply is set to a specific voltage, the error amplifier produces an output error voltage which changes Q_1's conduction so that the output voltage (E_O) is raised or lowered to the desired value.

The output voltage at the power supply shown in Figure 13 can therefore be varied by simply changing the reference supply voltage. This reference voltage is often obtained from a separate low-voltage regulated power supply which operates from a separate winding of the power transformer of the unregulated supply. This method allows a relatively low-voltage reference source to control a substantially higher output voltage. Normally, power supplies of this type are designed so that the output voltage is directly proportional to the reference voltage. Therefore, the output voltage can be reduced to zero by simply reducing the reference voltage to zero.

The output voltage of the power supply shown in Figure 13 can also be controlled, to a lesser extent, by varying the resistances of R_1 or R_2. If either of these resistors changes in value, the voltage at their junction will change. This will change the error voltage, which will cause Q_1 to change the output voltage. Power supplies which use this type of regulator are usually designed so that the output voltage is directly proportional to the value of R_2 and inversely proportional to the value of R_1.

The control of any power supply by means of an external control element is commonly referred to as programming, although the term "remote programming" is also used. Power supplies that feature a remote programming capability are usually equipped with suitable terminals or connectors which make it easy to apply or remove external control voltages or resistances. The controlling voltage or resistance is usually connected to the power supply through wires, and it may be located a considerable distance from the power supply. Remote programming makes it possible to place the power supply very close to the equipment that must receive power, and at the same time control the supply from a remote location which is convenient for the operator.

An extremely important factor to consider in any type of series regulator is the voltage drop, V_{CE}, across the pass transistor. We mentioned earlier that the output voltage of a series regulator is the difference between the unregulated supply voltage and the voltage drop across the pass transistor. The circuit must be designed so that this voltage drop never exceeds the maximum V_{CE} rating of the pass transistor. In a power supply that provides a low-power, fixed, output voltage, the pass transistor operates at relatively small values of V_{CE}. However, if the power supply is adjustable over a wide range of output voltages, this voltage drop may become rather large.

When it is intended that programming of the output voltage causes large changes in the output voltage, a technique called preregulation is used to prevent the voltage drop across the pass transistor from becoming excessive. In most applications of this technique, a monitoring circuit senses changes in the pass transistor voltage drop and drives circuitry that causes the unregulated input voltage to the regulator to vary. If the output voltage is reduced by changing the setting of an output control, then the value of E_{UN} is automatically reduced, resulting in only a small change in voltage drop across the pass transistor. In effect, preregulation provides coarse regulation of the input voltage and the conventional regulator circuitry provides fine regulation, using the preregulated voltage as its input.

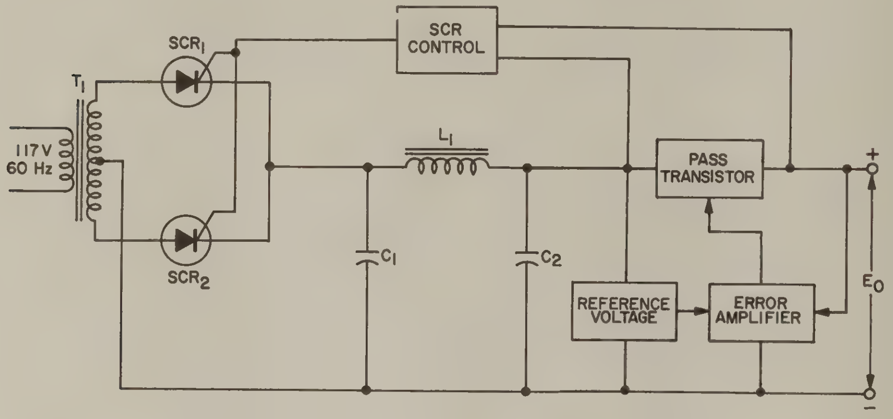


Figure 14

Figure 14 shows a power supply that uses one type of preregulator circuit. The voltage across the pass transistor is monitored by an SCR control circuit whose output signal controls the firing points of the pair of SCR's used as rectifiers in the unregulated power supply. (An SCR firing point is the instant when the gate signal's voltage amplitude and phase trigger the device into conduction.) The SCR control circuit advances or retards the firing point of the SCR's as the voltage drop across the pass transistor attempts to increase or decrease. This changes the amplitude of E_{UN} in such a way that the preregulator action minimizes changes in the pass transistor voltage drop.

The preregulation technique is especially useful for adjustable and programmable power supplies, although it is also desirable in fixed voltage power supplies where large changes in line or load conditions may occur during operation. Its main advantage, as illustrated by the example above, is that it maintains a reasonably constant voltage drop across the pass transistor. The normal regulator then provides close-tolerance regulation of the output voltage of the power supply.

In low-power regulators, preregulation may take the form of a simple zener diode regulator preceding the series regulator. The preregulator stabilizes the input to the regulator so that variations such as power supply ripple are minimized. This type of preregulation is useful in stabilizing bias voltages and currents so that the operating level of the regulator is not affected by input transients.

The following Practice Exercise questions cover the subjects which you have just studied. They are:

VOLTAGE REGULATORS

SHUNT VOLTAGE REGULATOR

SERIES VOLTAGE REGULATOR

12. To obtain regulation, a zener diode is connected in series with the load resistance. True or False?

13. The zener diode functions as a variable __________________________.

14. When using the zener diode of Figure 5 in the circuit of Figure 6 (R_1 and R_L are 1K ohm each), what is the maximum value of E_{UN} that can be safely regulated by D_1?

15. In Figure 7, what is Q_1 called?

16. In Figure 7, when E_{UN} increases, what happens to the conduction of Q_1?

17. In Figure 9, what is the function of D_1?

18. In Figure 9, what is the function of Q_2?

19. In Figure 9, what currents are carried by R_2?

20. In Figure 9, what happens to the Q_1 base current when the load resistance is changed from 100 ohms to 50 ohms?

21. In Figure 10, the reference signal is applied to the base of _____ and the output voltage sample is applied to the base of _____.

22. The arrangement of Q_3 and Q_1 in Figure 11 is called a ____.

23. In Figure 11 assume that the h_{fe} of Q_1 is 50 and the h_{fe} of Q_3 is 60. What is the total h_{fe} of the Darlington amplifier?

24. Why is the reference voltage obtained from a separate supply in Figure 13?

25. If E_O is adjusted to a lower level in Figure 14, the preregulator senses the attempted V_{CE} increase of the pass transistor and reduces the supply voltage to the regulator. True or False?

Switching Regulator

The regulators described up to this point may be referred to as linear regulators because the pass transistor conducts continuously over its linear operating range. This means that the transistor is dissipating power continuously, which reduces the efficiency of the power supply. We have noted that large requirements for power dissipation can also make it necessary to use a number of pass transistors in parallel, and to include elaborate heat sinking arrangements.

To reduce the dissipation problems and improve regulator efficiency, a type of regulator called the switching regulator is used in many high-power applications. In the switching regulator, the pass transistor serves as a switch that transfers energy from the unregulated supply to the load circuit. The switching action is controlled by the amplitude of the output voltage and a switching circuit that drives the pass transistor switch. A type of switching circuit driver that is often used is an oscillator, whose switching times are determined by the amplitude of an input error signal from the power supply's output voltage.

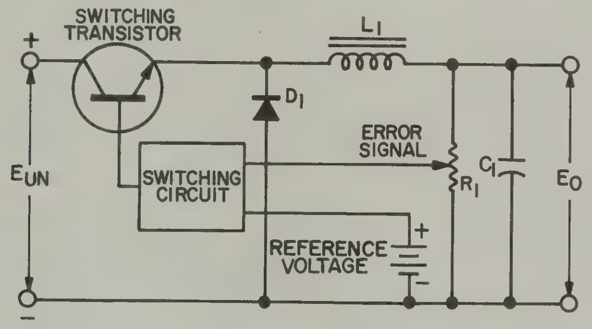


Figure 15

Figure 15 illustrates the basic operating principle of the switching regulator. The pass transistor (switching transistor) is used to supply energy from the unregulated supply to the load. Energy is stored in choke L during the on-time of the switching transistor. When the switching transistor is off, the choke provides an inductive kick which supplies energy through the diode to maintain the load current. In effect, the switching transistor supplies pulses of load current which are filtered by the inductor and capacitor. Switching frequencies of 5 kHz to 20 kHz are common. This results in rather high-amplitude ripple voltage, but it is not too difficult to filter properly because of its high frequency. However, it does make mandatory the use of capacitors that can adequately filter high-frequency signals.

The switching action is controlled by feedback from an output sensing circuit. The feedback from the output sensing circuit determines the width

A high-efficiency supply incorporating switching regulators is shown. This supply is available in voltage ratings from 4 to 28 volts, with power ratings from 308 to 375 watts. Load regulation is better than 0.1% for load changes from 15% to 100% of rated output, and 0.15% for load changes from 0 to 15% of rated output.

Courtesy Hewlett-Packard

of each pulse of the oscillator switching circuit which, in turn, determines the on-time of the ~~switching transistor~~.

If E_0 decreases, the output voltage from the output sensing circuit causes the switching circuit to increase the width of the driving pulse at the switching transistor base. The on-time of the switching transistor then increases to supply more energy to the choke which increases the output voltage. When E_0 increases, the on-time of the switching transistor is decreased to provide less energy to the choke and thus reduce E_0.

Pulse width modulation is a popular method of control in switching regulators. Variable frequency oscillators are also used, with the feedback voltage controlling the oscillator frequency, and thus the rate at which the pass transistor switches on and off. Other switching regulators use a high-sensitivity circuit to compare the output of the regulator with a fixed reference source and switch the pass transistor on and off according to the changes in output level. Because of the manner in which these regulators function, the choke, diode and filter capacitor are found in all switching regulators.

While switching regulators were used initially at higher operating voltages, from several hundred volts into the kilovolt range, they have also become popular in lower voltage power supplies, including those designed for semiconductor circuits, because of the savings in physical size and power dissipation. The switching regulator features extremely high operating efficiency because the switching transistor is either off or in saturation at all times. Therefore, very little power is dissipated across it, compared to the high-power dissipation of the linear power supply pass transistor that has a relatively large, constant collector-to-emitter voltage drop. Depending on the actual conduction time, efficiencies of 90% or more may be realized with switching regulators, compared to efficiencies of 25% to 50% for linear regulators. Because of this reduced operating power, the pass transistor dissipation requirements, including heat sinking, are reduced considerably. Switching regulators usually operate at high frequencies (5 to 20 kHz) to simplify filtering and permit use of a smaller choke. The initial cost of a switching regulator may be greater than that of a corresponding linear regulator in some applications, yet it may actually offer economy by eliminating the necessity of using the multiple pass transistors and elaborate heat sinks of the linear regulator.

CURRENT REGULATION

Up to now, all of the power supplies that we have discussed are designed to maintain a nearly constant output voltage as the load resistance and load current change. However, there are other situations where it is desirable to maintain a constant load current as the load resistance changes.

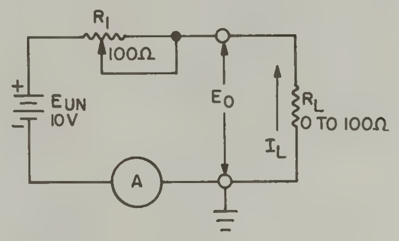


Figure 16

The theory of current regulation is quite simple and is illustrated by the circuit of Figure 16. To start, let's assume that R_1 is set to 50 ohms and R_L is selected to be 50 ohms. Since the sum of R_1 and R_L is 100 ohms and the unregulated voltage source E_{UN} is 10V, the load current I_L is

$$I_L = \frac{E_{UN}}{R_1 + R_L} = \frac{10}{50 + 50} = \frac{10}{100} = .1A = 100 \text{ mA}.$$

Now, if R_L is increased from 50 ohms to 60 ohms, it is merely necessary to decrease R_1 from 50 ohms to 40 ohms to maintain the load current constant. Also, if R_L is decreased from 50 ohms to 40 ohms, it is merely necessary to increase R_1 from 50 ohms to 60 ohms to again maintain the load current constant.

Going to extremes, for an R_L of 100 ohms, R_1 is set to zero ohms; for an R_L of zero ohms, R_1 is set to 100 ohms. We see that in Figure 16, as the load resistance varies, an automatic equal variation of R_1 in the opposite direction maintains a constant load current of 100 mA.

If we assume that R_1 is automatically adjusted in the proper direction to maintain I_L at 100 mA as R_L is varied, the output voltage, E_O, will vary from zero to 10 volts as R_L is varied from zero to 100 ohms. Under these conditions, the internal impedance of the current regulator would be infinite. This can be proven by substituting actual values into the internal impedance equation as follows:

$$Z_{int} = \frac{\Delta E_O}{\Delta I_L} = \frac{10}{0} = \infty$$

This equation shows that when the change in output voltage (ΔE_O) equals 10 volts and the change in load current (ΔI_L) equals zero, the internal impedance (Z_{int}) must be infinite (∞). However, this situation can occur only in an ideal current regulator which can maintain a load current that is absolutely constant. In a practical regulator, a small change in load current must always occur, giving the regulator a definite, but extremely high, internal impedance.

Analyzing Figure 16 further shows that there is a very definite limit to the regulating ability of the circuit. The circuit is limited to values of R_L from zero to 100 ohms. For values of R_L in excess of 100 ohms, the regulation ceases and the load current will decrease as R_L is increased. The limits of Figure 16 can be changed by changing the original design. For example, if E_{UN} is changed to 100 volts and R_1 is changed to 1K ohm, a constant load current of 100 mA can be maintained for all values of R_L from zero to 1K ohm. The important point is that all current regulators have a limit that is determined by the design of the circuit and this limit must not be exceeded.

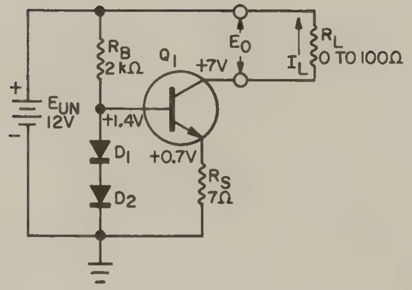


Figure 17

In order to make Figure 16 practical, it is necessary to replace R_1 with a device whose resistance automatically varies in direct opposition to variations in R_L. A simple way of doing this is shown in the circuit of Figure 17.

Here, D_1 and D_2 are silicon diodes that have a forward voltage drop of 0.7V each for a total of 1.4 volts across both in series. Thus, the Q_1 base voltage is fixed at 1.4 volts and does not vary. The resistance of R_B was chosen so that the current through the diodes is several times greater than the Q_1 base current, and variations of Q_1 base current do not affect the Q_1 base voltage.

To analyze Figure 17, remember that the circuit has been designed to maintain the load current, I_L, constant at about 100 mA for variations in load resistance, R_L, of zero to 100 ohms. Assuming that R_L is set to 50 ohms, and neglecting for the moment the relatively small base current of Q_1, the 100 mA of I_L through resistor R_S also causes the Q_1 emitter voltage to be +0.7 volt (with respect to ground). The 100 mA of load current through R_L causes E_O to be 5 volts and the Q_1 collector voltage to be +7.0 volts.

When R_L is changed from 50 ohms to 100 ohms, the load current through R_L and R_S attempts to decrease. However, a decrease of current through R_S

causes a decrease in the Q_1 emitter voltage, which increases the Q_1 base current, which increases the Q_1 collector current to almost its original value.

When R_L is changed from 50 ohms to zero ohms, the load current through R_L and through R_S attempts to increase. For these conditions, an increase in the Q_1 emitter voltage decreases the Q_1 forward bias, which decreases the Q_1 base current and decreases the Q_1 collector current to almost its original value.

The regulating ability of the circuit of Figure 17 is not perfect and a slight change in load current does occur as R_L is varied. The actual amount of load current change is determined by several factors, the most important of which are the value of R_S and the forward current gain of Q_1. The larger the value of R_S and the greater the forward current gain of Q_1, the better is the regulating ability of the circuit. However, as the value of R_S is increased, the value of the regulated load current decreases. This can be offset, in turn, by using an unregulated voltage source that has a greater output voltage. Notice, in Figure 17, that the unregulated voltage source, E_{UN}, is greater than the unregulated source of Figure 16. This is necessary to compensate for the voltage lost across the regulating circuit since the resistance of the regulating circuit can never be reduced to zero ohms.

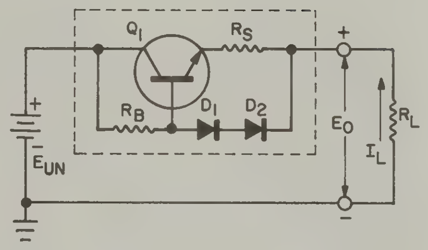


Figure 18

Although the circuit of Figure 17 is used for some applications, the arrangement of Figure 18 is more common. The two circuits are almost identical in operation with the major difference being the location of R_L with respect to the regulating circuit. In Figure 17, R_L is connected in series with the Q_1 collector, while in Figure 18, R_L is connected in series with the entire regulating circuit. An advantage of the Figure 18 circuitry is that R_L is connected to a common ground point in the circuit, while this is not true in Figure 17.

The arrangement of Figure 18 shows that the entire regulating circuit (enclosed in dashed lines) is in series with the load resistance. Therefore, to be a regulator, it must act as a variable resistance just like R_1 of Figure 16. In any current regulator, as in Figure 18, a current-sensing element (such as R_S) is used to monitor the load current. In more sophisticated current regulators that use additional stages of amplification, the current-sensing element may be located in another part of the circuitry. However, R_S must always be connected so that it does monitor the load current.

In most current regulators, R_S is connected in series with the full-load current. It is important, therefore, that the wattage rating of R_S be great enough that the heat it produces does not cause a resistance change. (In commercial regulators, the wattage rating of R_S is chosen to be about ten times the wattage that it is actually dissipating.)

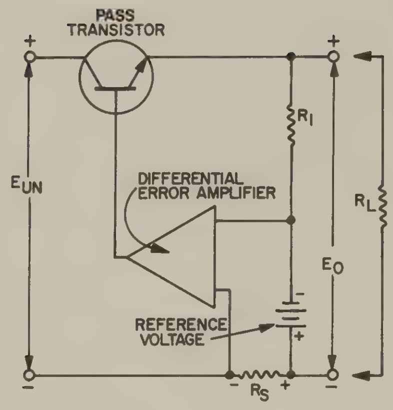


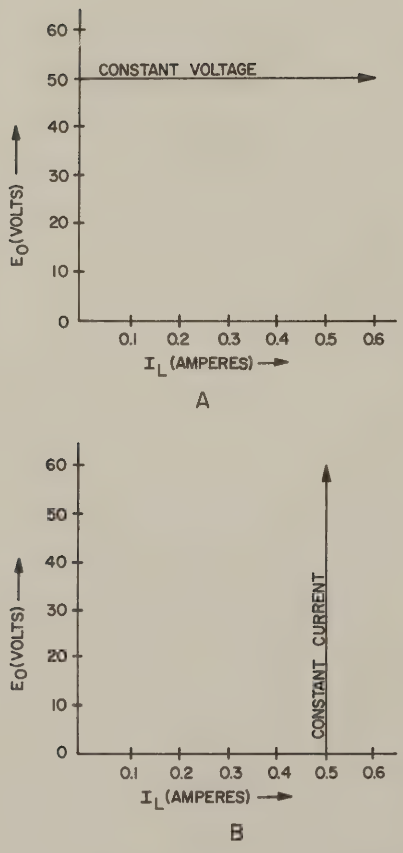
Figure 19

The current regulators of Figure 17 and 18 are suitable for use in noncritical applications where near-perfect regulation is not required. To improve their regulating ability, precision power supplies such as those used in laboratory applications include an error amplifier with the same basic arrangement as in the voltage regulators described previously. By amplifying the small voltage across the current-sensing resistor, the circuit offers a high sensitivity to small current changes, and therefore, much better regulation than the circuits shown in Figures 17 and 18.

Figure 19 shows a current regulator which utilizes a differential error amplifier. Note the similarity between this circuit arrangement and the voltage regulator of Figure 13. The difference is in the sensing method and the reference voltage connection. In most cases the current regulator requires more error signal amplification than a voltage regulator because of the extremely small signal voltage which appears across its sensing resistor (R_S). This resistor may have a value of only 2 or 3 ohms (to minimize its effect on load current) and its voltage drop for a load current of 100 mA would be only 200 or 300 millivolts.

In Figure 19, the error amplifier senses changes in the difference between the reference voltage and the voltage drop across R_S, and supplies a corrective signal to the base of Q_1. For example, if load current tries to increase, the conduction of Q_1 is decreased to hold the load current to its initial value. The reference voltage is usually variable to permit adjustment of the regulating level.

Notice that the output voltage, E_O, varies as the circuit regulates load current. For example, if the internal resistance of the pass transistor is increased to cause a decrease in load current, the voltage drop across the transistor increases and E_O decreases. Thus, a current regulator does not feature good voltage regulation.



A

B

Figure 20

Voltage and current regulators exhibit opposite characteristics, as shown by the curves of Figure 20. In Figure 20A, we see the output voltage of a perfect voltage regulator, supplying a constant E_O for all loads. This curve is a straight horizontal line from an open-circuit load (zero I_L) to a short-circuit load (infinite I_L). Since the change in E_O is zero for any change in I_L, the internal impedance of this perfect supply is zero.

The constant current curve of Figure 20B is a straight vertical line, representing zero change in current for all changes of E_O from zero to infinity. Since the change in I_L is zero, the internal impedance of this supply is infinite.

Power supplies are rarely designed to provide current regulation only. Most supplies that include a current regulator also include a voltage regulator. The circuits for both types of regulators are very similar.

AUTOMATIC CROSSOVER SUPPLIES

By combining the outputs of the error amplifiers of a voltage regulator circuit and a current regulator circuit, a pass transistor can be driven to provide a constant voltage or constant current output. An automatic crossover supply is a power supply that will provide either voltage regulation or current regulation of its output. The mode of regulation (either voltage or current) depends on load conditions, and the supply will automatically switch from current regulation to voltage regulation at a point of operation that is determined by the setting of its output controls. A typical automatic crossover supply may be represented by Figure 21.

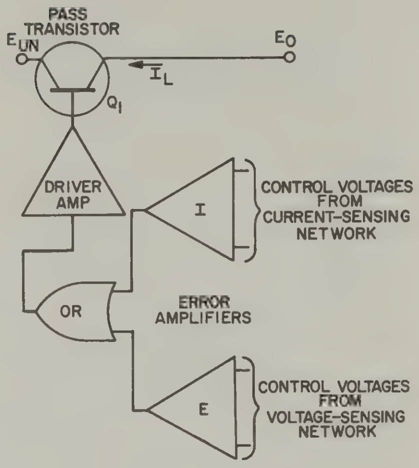

PASS TRANSISTOR
E_{UN}
E_O
I_L
Q_1
DRIVER AMP
I
CONTROL VOLTAGES FROM CURRENT-SENSING NETWORK
OR
ERROR AMPLIFIERS
E
CONTROL VOLTAGES FROM VOLTAGE-SENSING NETWORK

Figure 21

Notice that the pass transistor, Q_1, is controlled by a driver amplifier controlled by an OR gate which is, in turn, controlled by two error amplifiers. In this OR arrangement, the error amplifier which produces the larger output signal controls the pass transistor. Therefore, the pass transistor is allowed to regulate in only one mode at a time.

The input voltages applied to the error amplifiers are usually obtained from appropriate networks which sense the output voltage and current provided by the power supply. The networks also include controls which are used to adjust the input voltage levels applied to the error amplifiers. These controls make it possible to set the exact point at which the output from each amplifier will take control of the pass transistor. In other words, the reference inputs to the error amplifiers are adjusted to set the desired limiting levels for current and voltage control. This automatically sets the maximum output voltage (E_0) and load current (I_L) that the circuit provides. It also establishes a crossover point at which the circuit will switch between the constant voltage and constant current modes of regulation.

The OR gate is usually nothing more than two emitter-coupled transistors, as shown in Figure 22. The transistor which receives the larger input voltage assumes control and forces the other transistor to cut off. The output of the OR circuit is taken from the common emitter resistor; therefore, the controlling (conducting) transistor determines the amplitude of the output control voltage applied to the pass transistor. Notice that an additional driver amplifier is used to step up the output voltage to a level sufficient to drive the pass transistor.

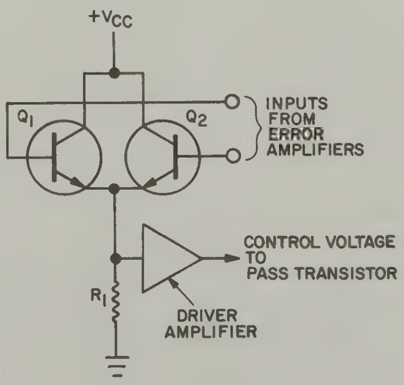

$+V_{CC}$
Q_1
Q_2
INPUTS FROM ERROR AMPLIFIERS
CONTROL VOLTAGE TO PASS TRANSISTOR
R_1
DRIVER AMPLIFIER

Figure 22

$R = \frac{V}{I}$

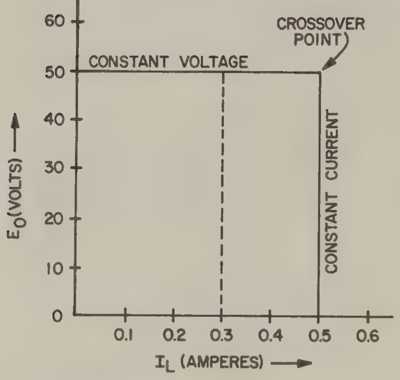


Figure 23

To illustrate the action in this circuit, the constant voltage and constant current curves of Figure 20 are combined in Figure 23. The reference current level is assumed to be set to 0.5 ampere and the reference voltage level to 50 volts. Once the controls are set, the action of the regulator will depend on the load resistance connected across the E_0 terminals.

The crossover resistance with the values selected is 100 ohms, determined by dividing the reference value of E_0 (50 volts) by the reference value of I_L (0.5 ampere). When the load resistance is greater than this crossover resistance (from infinity to 100 ohms), the regulator operates in the voltage mode. When the load resistance exceeds the crossover resistance, the sensed value of I_L is below the reference current level, making the output of the current error amplifier small, and therefore blocking it in the OR gate. The output from the voltage error amplifier assumes control at this time since it is larger.

If the load resistance is less than the crossover resistance (from zero to 100 ohms), the current error amplifier takes control of the regulator since its output becomes larger. The voltage error amplifier signals are therefore blocked by the OR gate, and the load current is held constant by the current regulating action.

The automatic crossover supply is free from overload for all load conditions from open to short circuit. If the voltage and current regulators are carefully designed, the voltage and current curves are practically straight lines, and regulation is excellent in both the voltage and current modes.

The crossover point depends on the settings of the reference controls. For example, the dashed vertical line in Figure 23 shows the effect of reducing the current level setting to 0.3 ampere and leaving the voltage level setting at 50 volts. This shifts the crossover resistance to approximately 166 ohms. The supply now operates in the voltage mode for all load resistances from open circuit down to 166 ohms, and in the current mode for load resistances from 166 ohms to a short circuit.

Crossover regulation is used in most laboratory-type supplies. To give an indication of the operating mode, signals from the error sensors can be fed to indicators on the panel of the power supply.

PROTECTIVE CIRCUITS

Protective circuits are an important part of modern regulated power supplies. The power supply itself must be protected from the effects of

The following Practice Exercise questions cover the subjects which you have just studied. They are:

VOLTAGE REGULATORS

SWITCHING REGULATOR

CURRENT REGULATION

AUTOMATIC CROSSOVER SUPPLIES

26. In a switching regulator, the pass transistor serves as a __________ to control the transfer of energy from the unregulated supply to the load.

27. In Figure 15, the diode conducts when the switch is (a) on, (b) off.

28. If the output voltage of a switching regulator attempts to decrease, the on-time of the switching transistor must increase to keep the output at the desired level. True or False?

29. What is the main advantage of a switching regulator compared to a linear regulator?

30. In Figure 16, R_L is chosen to be 25 ohms. What must be the resistance of R_1 to maintain the load current constant at 100 mA?

31. In Figure 17, what is the function of D_1 and D_2?

32. In Figures 17 and 18, what component is the current-sensing element?

33. The internal impedance of a perfect current regulator is zero. True or False?

34. In an automatic crossover supply, what determines the crossover point?

35. In an automatic crossover supply, if the load resistance is less than the crossover resistance, the circuit operates in the voltage regulating mode. True or False?

36. In the current limiter of Figure 24, the voltage drop across ____ determines the limiting action.

37. Current limiting occurs in Figure 24 when D_2 (a) conducts, (b) does not conduct.

38. The curve of Figure 27 illustrates a form of current limiting called ______________ limiting.

excessive load current. Conventional fuses and circuit breakers provide a certain amount of protection. However, the thermal characteristics of a fuse or the mechanical action of a breaker may not be quick enough to prevent the delicate junctions of semiconductor components from being damaged.

Overvoltages can prove destructive to the load, and must also be considered in the protective scheme. Even a small overvoltage can result in destruction of the circuits connected to the supply.

In addition, there is always the problem of overheating within the supply, which can occur where large load currents are involved. Sensing devices which shut down the supply in case of overheating are therefore an important consideration.

Current Limiting

A current limiting circuit senses the load current and operates to lower the output voltage if this current reaches some predetermined value. The automatic crossover power supply features automatic current limiting by virtue of its crossover into the current limiting mode when load current reaches the crossover level. Current limiting circuits can be added to other voltage regulators to provide similar action.

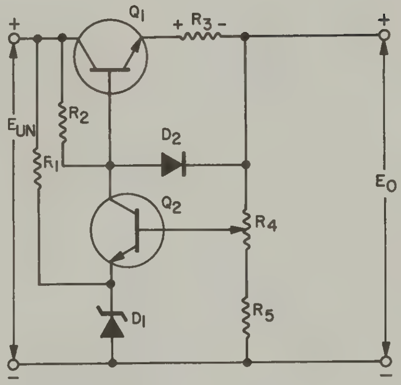


Figure 24

Figure 24 shows a current limiter added to a voltage regulator similar to that of Figure 9. Limiting is provided by diode D_2 and current-sensing resistor R_3. The limiting level is set by the value of R_3 and the forward conduction voltage of D_2. Resistor R_3 can be made variable to permit adjustment of the limiting level.

For load currents below the limiting level, D_2 does not conduct, and the circuit provides normal voltage regulation. If load current increases, there is a corresponding increase in voltage across R_3. When the drop across R_3 reaches the forward conduction voltage of D_2, the diode conducts and applies reverse bias from R_3 to the base of Q_1. This reduces the conduction of Q_1 to limit the load current.

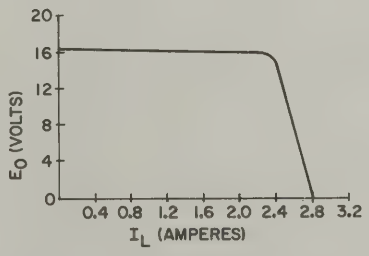


Figure 25

The limiting action is illustrated by the curve of Figure 25. Here, the normal voltage regulation is shown by the almost straight horizontal part of the curve for load currents from zero to over 2 amperes. Limiting occurs at this point, as shown by the sharp drop in the curve. The dropoff shows that the

A group of miniature power supply modules is shown. These units are available in a variety of operating voltage ranges between 5 and 28 volts, and feature automatic short-circuit protection.

Courtesy Sorensen Company
Unit of Raytheon Company

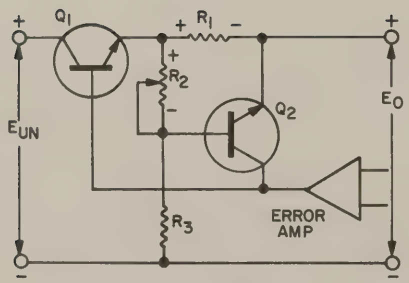


Figure 26

output voltage decreases rapidly, due to the increase of internal resistance in Q_1 caused by the rising reverse bias across R_3. Normal operation is restored when the cause of the overload is corrected.

A type of current limiting, called current foldback limiting, occurs in the circuit of Figure 26. During normal operation, Q_2 is reverse biased by the voltage across R_2 and therefore has no effect on the operation. Pass transistor Q_1 regulates the output voltage in the usual manner, under control of the signal from the error amplifier.

If load current increases, the voltage across R_1 increases. At the limiting level, the voltage across R_1 exceeds the voltage across R_2, and the Q_2 becomes forward biased. When Q_2 conducts, the base of Q_1 is connected through the Q_2 collector-emitter junction to the negative side of R_1, which reverse biases Q_1, cutting it off. This rapidly decreases the output voltage and current to insignificant values.

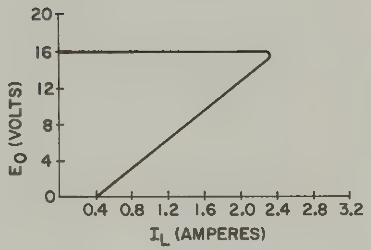


Figure 27

A typical foldback curve is illustrated in Figure 27. As in Figure 25, the normal voltage regulation is indicated by the horizontal line for load currents, from zero to approximately 2 amperes. The foldback occurs at this point, rapidly reducing the output voltage and load current. The advantage of this system is the quick removal of the current and voltage to protect the load and regulator circuits. Normal operation is restored when the overload is removed.

Overvoltage Protection

Just as the power supply requires protection from load failures that cause excessive current, the load must be protected from supply failures that can cause excessive output voltage. For example, a shorted pass transistor will apply the full, unregulated supply voltage to the load terminals. In many circuits, this would result in destruction of the load components.

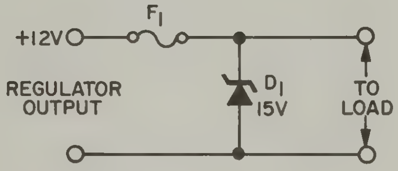


Figure 28

A simple, overvoltage protection device is illustrated in Figure 28. A zener diode is connected in series with a fuse across the regulator output terminals. The load is connected in parallel with the diode, which has a voltage rating just above the normal operating voltage of the circuit.

Diode D_1 has no effect on circuit operation as long as the output voltage is normal. But if this voltage rises above the zener voltage, the diode conducts. This causes sufficient current to blow the fuse and disconnect the load from the power supply.

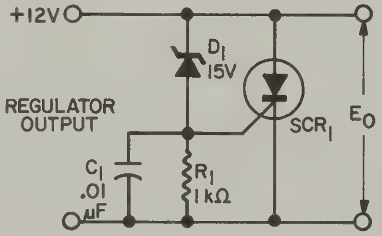


Figure 29

Although the simple arrangement of Figure 28 is effective, it requires a certain time for the fuse to blow, and this time lag may be long enough to permit serious damage to the load. The circuit of Figure 29 provides much quicker protection, and is very popular in regulator units. This arrangement is called a "crowbar circuit."

The crowbar circuit is connected across the output terminals, but has no effect on operation as long as the output voltage is normal. Zener diode D_1 has a voltage rating slightly greater than the normal value of E_O. If the value of E_O rises above the rating of D_1 (15 volts), D_1 conducts through R_1. The resultant voltage drop across R_1 forward biases SCR_1, turning it on. When the SCR begins conducting, it shorts the output terminals and removes the voltage from the load.

Since the SCR shown in Figure 29 shorts the output terminals when it conducts, it is capable of conducting very high currents which could possibly damage the regulator circuit. This type of crowbar circuit is therefore used only with those power supplies that contain fast-acting fuses or appropriate current limiting circuitry.

Once the SCR begins conducting, it remains on until its anode voltage is removed. This is simply a matter of turning off the supply, correcting the cause of the overvoltage, and turning on the supply again.

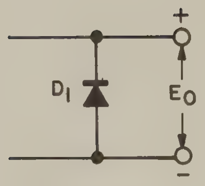


Figure 30

Reverse Voltage Protection

The arrangement of Figure 30 is used to protect the load and power supply from reverse voltages. Diode D_1 is a conventional silicon diode connected in the reverse direction across the output terminals of the supply. For normal voltages, the diode does not conduct and has no effect on the operation. When a reverse voltage occurs, the diode conducts and limits the reverse voltage to about 0.7 volt, its forward conduction voltage. This arrangement must also be used with supplies that limit current or have fast-acting fuses.

Thermal Protection

One problem common to all power supplies is that of heat dissipation. Thermal overload protection is provided in some high-power regulators by the use of thermal cutouts that sense dangerous temperature levels and open the power supply output connections to prevent damage. The most common method of using thermal cutouts involves the cutout device to the heat sink of the pass transistor. If the heat sink temperature rises above a predetermined safe level, the thermal cutout opens, shutting down the power supply until there is sufficient cooling to deactivate the cutout. In some circuits the action also triggers an alarm, such as an indicator lamp, on the front panel of the power supply.

As shown later in this lesson, integrated circuit regulators are usually designed with built-in thermal shutdown circuitry. These regulators commonly use components with appropriate temperature coefficients as a means of guarding against problems related to heat dissipation.

Applications of Protective Circuits

Figure 31 is the schematic diagram of a regulator equipped with several protective circuits. This regulator is also of interest because it is arranged to

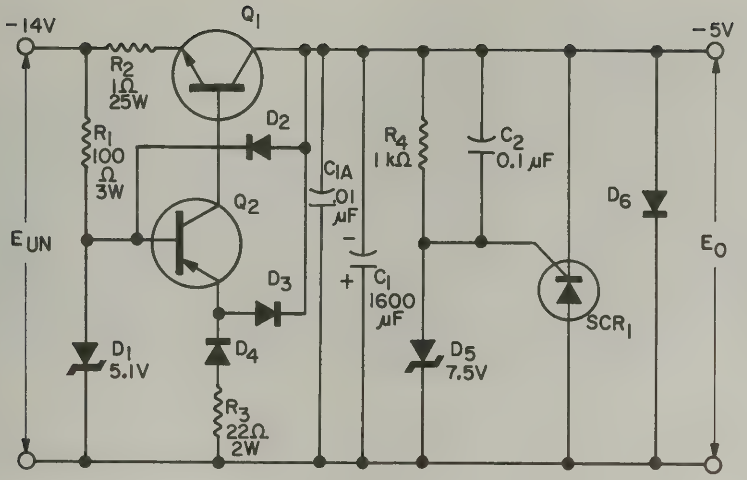


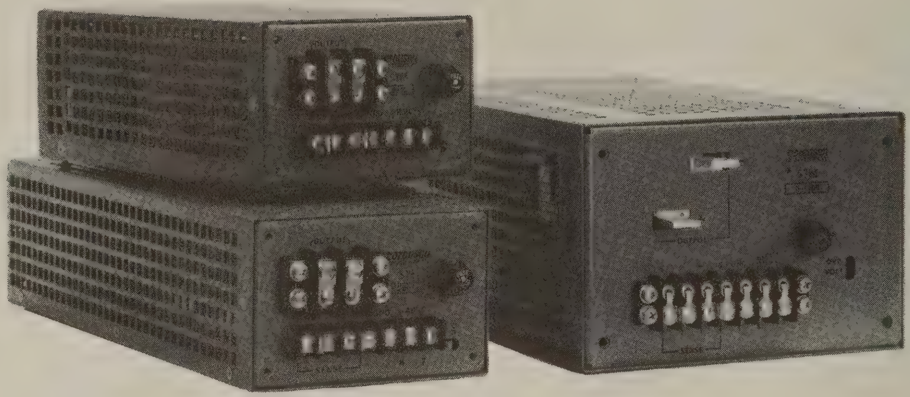
Figure 31

provide a negative output voltage. Compared to the regulators illustrated previously, the negative output voltage regulator requires reversal of the voltage sensitive components (diodes, transistors, etc.), but it is identical in all other respects to a positive output voltage regulator. Many regulated power supplies use combinations of positive and negative regulators, connected to separate supply sources, to provide the operating voltages for various circuits in the load.

The regulator of Figure 31 is designed to provide a −5 volt dc output for circuits employing IC's. The unregulated input is obtained from a −14 volt supply. Q_1 is the pass transistor, driven by amplifier Q_2. The base of Q_2 is held at −5.1 volts by reference zener diode D_1. The output voltage is sampled by a voltage divider consisting of D_3, D_4 and R_3. Since the forward conduction resistance of the silicon diodes causes a drop of approximately 0.7 volt each, the emitter of Q_2 is 0.7 volt less negative than the negative output terminal of the supply. For normal operation, this places the Q_2 emitter at −4.3 volts. The −5.1 volt reference on its base forward biases Q_2, to provide a path for the Q_1 base current.

If E_O varies, the emitter voltage of Q_2 also varies in the same direction because of the constant volt drop across D_3. This changes the conduction of Q_2, which changes the Q_2 collector and Q_1 base voltage, which changes the conduction of Q_1.

Capacitor C_1 removes ripple in the regulated output, and capacitor C_{1A} absorbs voltage spikes that may occur when a load is connected to, or removed from, the output terminals, providing a measure of overvoltage protection.



These modular power supplies feature switching regulator circuitry to achieve high efficiencies and resultant high-power ratings with compact size.

Courtesy Sorensen Company
Unit of Raytheon Company

Overvoltage protection is also provided by the crowbar circuit consisting of SCR_1 and D_5. Zener diode D_5 has a voltage rating of 7.5 volts, and therefore does not conduct during normal operation. With no voltage drop across R_4, the gate and cathode of SCR_1 are at the same potential, and SCR_1 does not conduct. If E_O rises above -7.5 volts, D_5 conducts, and the resultant voltage drop across R_4 raises the SCR_1 gate voltage and SCR_1 begins conducting, shorting the load terminals, which protects the load. To restore proper operation the power supply must be turned off, the cause of the overvoltage corrected, and the supply turned on again.

Diode D_6 provides reverse voltage protection, as explained for Figure 30. If a positive voltage appears across the output terminals, the diode conducts to short out this voltage. Reverse voltage is limited to about 0.7 volt, the forward voltage drop across the diode. Diode D_6 protects against reverse voltage spikes as well as reverse voltages due to incorrect circuit connections or circuit defects.

Resistor R_2 holds the Q_1 collector current at a reasonable value for normal ranges of load current. Short-circuit current limiting is provided by D_2. For normal operation, this diode is reverse-biased by the circuit voltages and it has no effect on operation. If the load terminals are shorted, diode D_2 conducts to form a current path around the pass transistor and limit the current to a safe value.

A short circuit across the load tends to pull down (decrease) the supply voltage at the input to the regulator. While Q_2 tries to maintain the output voltage, the decreasing voltage across R_1 and D_1 reaches a point at which D_1 drops out of its zener region. This causes Q_2 to cut off, which, in turn, cuts off Q_1. With these transistors cut off, the load current must pass through a path consisting of R_1 and D_2. R_1 limits the short-circuit load current to about 150 mA and the output voltage to about 0.3 volt until the short circuit is removed. Thus, the circuit provides a form of current foldback limiting.

INTEGRATED CIRCUIT REGULATORS

Integrated circuits have had an important effect on the design of regulator systems. In some hybrid regulator systems, the sensing circuits and drivers are made up of integrated circuit amplifiers to provide savings in cost and size. Another advantage of IC's is high stability, made possible by the closely matched elements of IC chips.

Most IC manufacturers now include a variety of complete regulator circuits in their product lines. The power supply designer can select from the variety of IC's available to produce pratically any type of regulator system desired. For some low-power applications, the complete regulator assembly may be contained in one integrated circuit package. For higher power service, the IC circuitry can be used to drive discrete pass transistors and other components.

Figure 32 shows both a block diagram and complete schematic diagram of the MC1566/MC1466 integrated circuit regulator manufactured by Motorola. This versatile unit provides current and voltage regulation with automatic crossover at tolerances close enough to meet most laboratory standards. Line and load voltage regulation ratings are 0.01% + 1.0 millivolt, and current regulation is 0.1% + 1.0 mA. The current and voltage outputs are adjustable, and full short-circuit protection is provided. The unit is available in a standard TO-116 dual in-line package.

In Figure 32, the functions of the various sections of the chip are identified by the block diagram above the schematic. The unregulated voltage applied to the input (pins 14 and 7) is preregulated by the internal voltage regulator to provide a highly stable reference voltage for all circuits in the regulator. The reference voltage source actually consists of a differential amplifier which controls a series pass transistor and its driver transistor, as shown in the schematic portion of Figure 32. Temperature stability is obtained by using temperature compensated zener diodes and forward-biased diodes in the base circuits of the two transistors (Q_1 and Q_2) that make up this differential amplifier. The Q_1 collector voltage is applied directly to the base of transistor Q_3, whose output controls the pass transistor (Q_4). The regulated

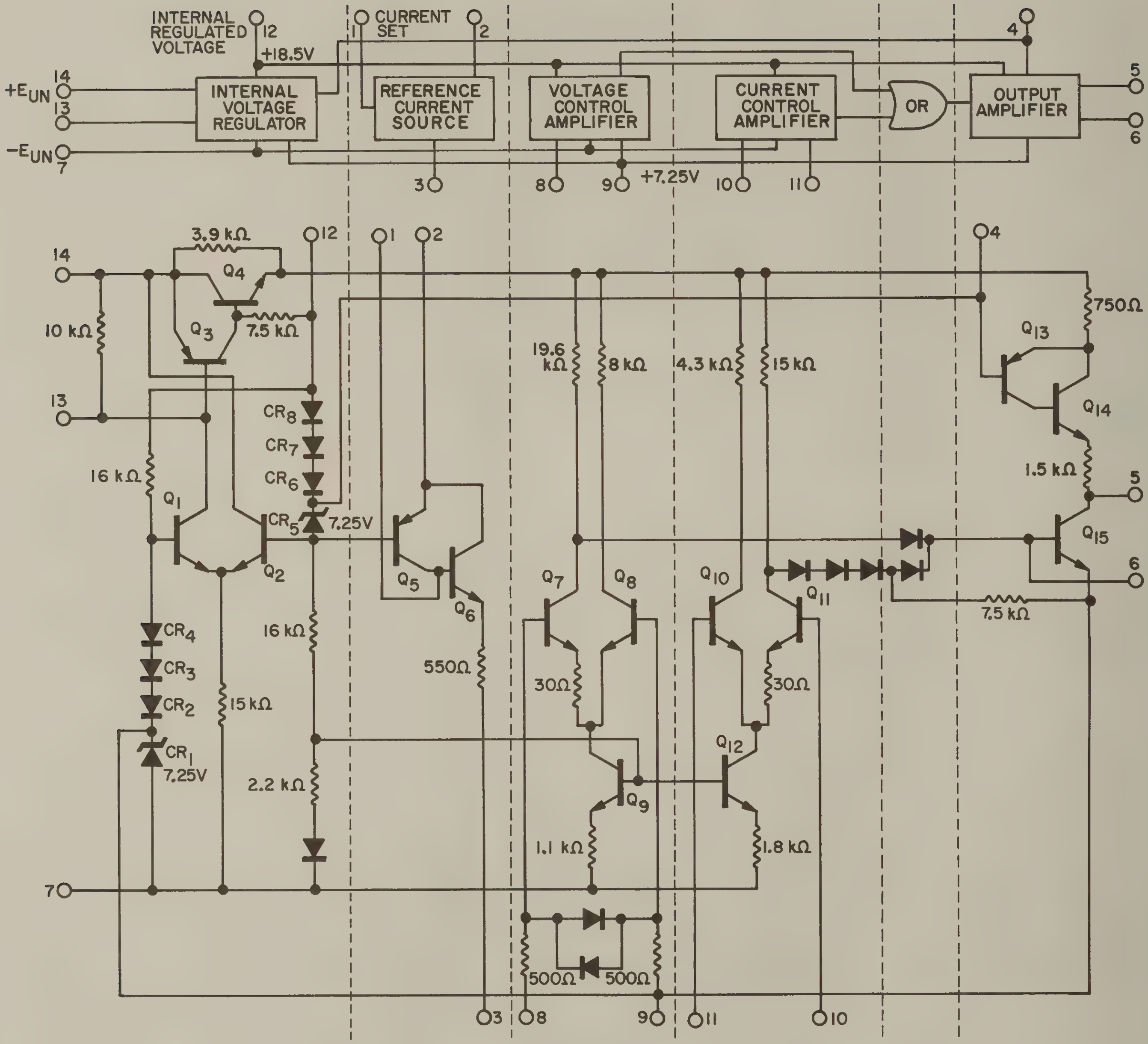


Figure 32

voltage appearing at the emitter of Q_4 is then applied to the remaining circuits of the IC.

The second section of the voltage regulator is a constant current source used to generate a reference voltage that is compared with the output voltage controlled regulator. The amount of constant current produced by the circuit is determined by the value of an external resistor which must be connected between pins 12 and 2. Another external resistor is normally connected between pin 3 and circuit ground, and pin 3 is usually shorted to pin 8. The constant current produced by the circuit therefore flows through pin 3 and also through the external resistor. The voltage developed across this resistor serves as the reference potential and it is applied directly to the voltage control amplifier through pin 8. Since the current through this external resistor is constant, the reference voltage produced can be effectively changed by adjusting the value of the external resistor.

The voltage control amplifier forms the third section of the IC. This circuit uses a differential amplifier to compare the reference voltage at pin 8 with the voltage at pin 9, which is connected to the circuit to be regulated and is the positive output terminal of the regulator. If the output voltage at pin 9 is higher or lower than the reference voltage at pin 8, the differential amplifier sends an appropriate control voltage from Q_7 collector to one side of the OR gate (fifth section), which causes the output amplifier (sixth section) to conduct more or less until the output voltage is equal to the reference voltage. The voltage control differential amplifier is protected from excessive differential voltage by two diodes and two resistors that are connected between pins 8 and 9.

The remaining input to the OR gate is provided by the current control amplifier (fourth section). This circuit is almost identical to the third section voltage control amplifier. The purpose of the current control amplifier is to limit the output current of the regulator. The operation of this circuit is controlled by external resistors. The reference input, pin 10, comes from either a potentiometer's movable contact or a junction point of a voltage divider connected between pins 9 and 12. The pin 11 input is connected to an external current-sensing resistor that is in series with the load. When changes of voltage are produced across the sensing resistor, the current control amplifier output at Q_{11}'s collector sends a control voltage to the OR gate. If this signal to the OR gate is larger than the signal from this voltage control amplifier, it becomes the OR gate output, causing the output amplifier to conduct less, limiting the output current. By adjusting the reference input voltage to the current control amplifier, the maximum output current supplied by the voltage regulator can be continuously varied over a wide range.

The OR gate is simply an arrangement of diodes which combines the outputs of the voltage and current control amplifiers. The voltages applied to the OR gate determine whether the OR gate output voltage will cause the output amplifier to produce a constant (regulated) output voltage or a constant (limited) output current.

The output amplifier responds directly to the signal produced by the OR gate; however, the circuit is not designed to directly pass the output load current. Instead, the output amplifier is constructed so that it can control the operation of an external series pass transistor. Transistors Q_{13} and Q_{14} provide a constant current temperature compensated source to transistor Q_{15}. The conduction of Q_{15} is directly controlled by the OR gate, and the Q_{15} collector output at pin 5 supplies the signal to the base of the external pass transistor. Any unwanted high frequencies may be suppressed by connecting a suitable feedback network between pins 5 and 6.

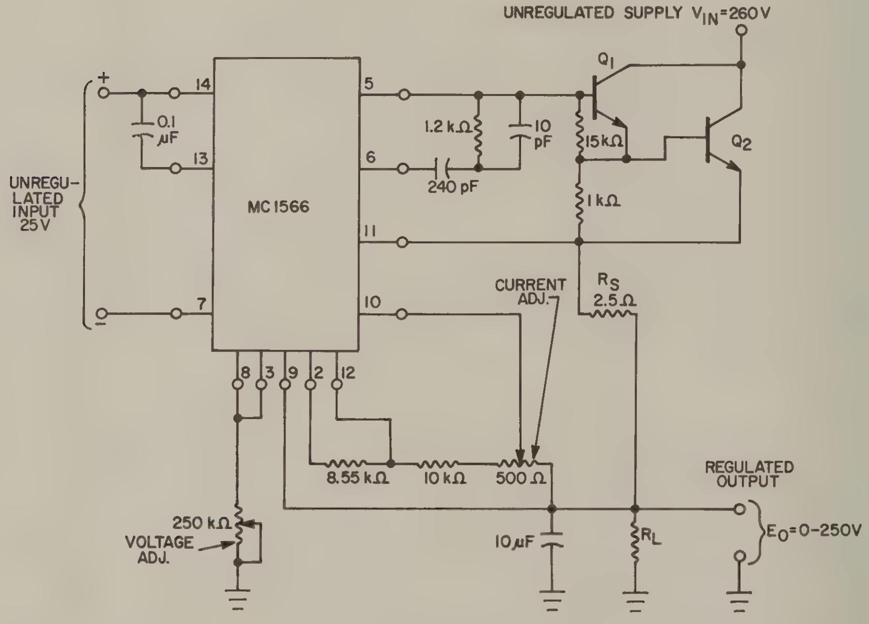


Figure 33

Integrated circuit regulators, like the one just described, can usually be connected for a variety of applications. The methods of connection are usually given in the specification sheets supplied by the manufacturer. For example, the method recommended for connecting the MC1566/MC1466 regulator to provide a 0 to 250-volt regulated output at 0.1 ampere maximum is illustrated in Figure 33. This circuit is arranged so that maximum output current is also adjustable from 0 to 0.1 ampere. This is accomplished by using a 500-ohm potentiometer to vary the voltage applied to pin 10 to control the operation of the current control amplifier in the regulator circuit. The maximum limit of 0.1 ampere is determined by the setting of the 500Ω potentiometer. The error signal to the current control amplifier is developed across current-sensing resistor R_S. A 250K ohm potentiometer is used to adjust the output voltage. The reference voltage developed across the potentiometer varies in proportion to its resistance. The output voltage obtained is directly proportional to the reference voltage.

Also notice that two external transistors are used to control the output of the regulator. The first transistor (Q_1) drives the second transistor (Q_2) Darlington fashion, to control the current and voltage supplied to the load (R_L in Figure 33). Although the MC1566 integrated circuit regulator operates at relatively low voltages, it is capable of indirectly regulating a much higher voltage (250 volts), as shown. This is possible because the current and voltage levels sensed by the integrated circuit regulator are only small differential input signals and the output amplifier stage is subjected only to the low voltages which exist at the emitter-base junction of the series pass transistors.

The unregulated input voltage (25 volts dc) for the MC1566 integrated circuit regulator is usually a rectified and filtered voltage obtained from a low-voltage winding of a power transformer. A higher voltage winding on the same transformer could be used to provide the unregulated high voltage (260 volts dc) which is applied to the external transistors. The high voltage would, of course, also be rectified and filtered.

REMOTE SENSING

In general purpose supplies, line and load regulation ratings of 0.1% are typical. Laboratory supplies are designed to provide precise voltages and currents that can be held almost constant despite large changes in line or load conditions. Regulation ratings on the order of 0.001% are featured in these supplies.

The regulation we are mainly concerned with is the regulation at the load. In many instances, the power supply and load are integral units and the regulation at the supply terminals and at the load are one and the same. But, if the load is separated by some distance, the losses in the connecting wires can result in a sizable difference between the supply voltage and load voltage. Then, the regulator circuits may not accurately sense the load voltage to provide the desired control.

One method of overcoming this problem is to remove the regulator from the power supply and place it at the load. This approach is practical with integrated circuit regulators, as already mentioned. Another method is to separate the sensing terminals from the load terminals of the supply. This feature, called remote sensing, is provided in many power supplies.

In a remote sensing system, the load draws its operating current from the + and − load terminals in the usual way. The sensing signal that controls the regulator is fed from the load to the supply through a separate pair of leads. Because the sensing circuits operate at low current there is very little loss across these leads. Therefore, the sensing signal received by the regulator is a truer indication of the condition at the load.

Power supplies that include this feature usually have a provision for selecting either remote sensing or normal sensing at the supply output. The selection is made by removable links or jumpers on the terminal strip.

SUMMARY

We have looked into the subject of regulated power supplies with an eye to the general principles of regulation and the basic circuits used to achieve good regulation. The actual circuits used in commercial units will, of course, vary according to the requirements of the system and the ingenuity of the designer.

Regulated power supplies are often designed to provide either a constant output voltage or a constant output current; however, some power supplies are capable of doing both. Regulation is usually accomplished by using either a series- or a shunt-type regulator. Switching regulators are also used where maximum regulator efficiency is required.

Remote programming is a feature available with many power supplies. With remote programming, the output level can be varied from a remote location by adjustment of a potentiometer or reference voltage source. This feature is desirable in industrial control or testing systems.

Some regulated supplies are designed to provide a fixed output. This is the usual case when the supply is designed as an integral part of the unit to which it supplies power. Other supplies feature an output voltage adjustment and, in some cases, a current level adjustment for current limiting or current regulation. The ultimate in control is the laboratory supply, which provides precise voltages and currents for design and test applications.

Protective measures are an important feature of every supply. The protective circuits that we have described are used in various combinations to guard against destruction of the load and the supply. The more delicate the circuits, the more extensive the protective circuitry must be. The primary function of the overload circuit is to shut down the supply in the event of a defect; some units feature visual alarms to indicate failure.

The following Practice Exercise questions cover the subjects which you have just studied. They are:

PROTECTIVE CIRCUITS
  CURRENT LIMITING
  OVERVOLTAGE PROTECTION
  REVERSE VOLTAGE PROTECTION
  THERMAL PROTECTION
  APPLICATIONS OF PROTECTIVE CIRCUITS
INTEGRATED CIRCUIT REGULATORS
REMOTE SENSING

39. The circuit of Figure 29 is called a ______________ circuit.

40. What happens to E_O in Figure 29 when SCR_1 conducts?

41. How is the crowbar circuit of Figure 29 restored to readiness after the SCR has started conducting?

42. D_6 of Figure 31 is used to provide current limiting. True or False?

43. D_5 in Figure 31 conducts when E_O reaches a voltage of ____ volts.

44. What is the purpose of transistors Q_5 and Q_6 in Figure 32?

45. The voltage control amplifier is basically a __________________ amplifier.

46. The current control amplifier shown in Figure 32 is used to limit the output current of the regulator. True or False?

47. Resistor R_S in Figure 33 is used to limit the output voltage to 250 volts. True or False?

48. The 250K ohm potentiometer in Figure 33 effectively varies the reference voltage of the regulator. True or False?

ESSENTIAL SYMBOLS AND EQUATIONS

E_S	source voltage
E_{UN}	unregulated voltage
I_L	load current
I_B	bleeder current
Z_{int}	power supply internal impedance
V_{in}, V_{IN}	input voltage, IC
V_Z	zener voltage
V_{ZT}	zener test voltage

$$\% \text{ Reg} = \frac{E_{\text{NO LOAD}} - E_{\text{FULL LOAD}}}{E_{\text{FULL LOAD}}} \times 100 \tag{1}$$

$$I_L = \frac{E_S}{Z_{int} + R_L} \tag{2}$$

PRACTICE EXERCISE SOLUTIONS

1. (c) load resistance and load current are fairly constant.

2. True

3. $$\% \text{ Reg} = \frac{E_{\text{NO LOAD}} - E_{\text{FULL LOAD}}}{E_{\text{FULL LOAD}}} \times 100$$

$$= \frac{24 - 20}{20} \times 100 = \frac{4}{20} \times 100 = 20\%$$

4. The power transformer, the filter and the rectifiers.

5. (a) higher output voltage if the ac input voltage increases.

6. (a) the resistance of R_B is decreased.

7. (a) line regulation.

8. Shunt and series regulators.

9. pass

10. (b) decrease.

11. decrease

12. False—A zener diode is connected in parallel with the load resistance.

13. resistance

14. 35 volts. Since the regulated voltage, E_O, is 10 volts and R_L is 1K ohm, the load current is 10 mA. From Figure 5, the maximum zener current is 15 mA. With 25 mA through the 1K ohm of R_1, the maximum voltage drop across R_1 is 25 volts. Therefore, the maximum value of E_{UN} voltage drop across R_1 is 25 volts. Therefore, the maximum value of E_{UN} is $E_{R_1} + E_O = 25 + 10 = 35$ volts. Any higher value of E_{UN} would cause excessive zener current and probable damage to the diode.

15. Q_1 is called the pass transistor or pass element.

16. The regulator action causes the conduction of Q_1 to decrease.

17. In Figure 9, D_1 holds the Q_2 emitter voltage constant.

18. The function of Q_2, in Figure 9, is to amplify any change of voltage that appears at its base.

PRACTICE EXERCISE SOLUTIONS (Continued)

19. The Q_1 base current and the Q_2 collector current are both through R_2.

20. The Q_1 base current increases. When the load resistance is changed from 100 ohms to 50 ohms, the load current increases from 250 mA to 500 mA. Therefore, the Q_1 base current must increase from 5 mA to 10 mA.

21. Q_2; Q_1

22. Darlington amplifier

23. 3000.

24. To permit the output voltage to be adjusted to zero.

25. True

26. switch

27. (b) off.

28. True

29. The switching regulator affords greater efficiency.

30. R_1 must be 75 ohms.

31. D_1 and D_2 produce a fixed reference voltage at the base of Q_1.

32. R_S.

33. False—In a perfect current regulator, the change in current is zero for any change in voltage. Thus, the dynamic impedance is infinite. ($\Delta E/\Delta I = \Delta E/O = \infty$)

34. The settings of the voltage and current level controls establish the crossover point.

35. False—The circuit operates in the current regulating mode when the load resistance is less than the crossover resistance.

36. R_3

37. (a) conducts.

38. foldback

39. crowbar

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4141 BELMONT AVENUE, CHICAGO, ILLINOIS 60641

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7410A
EXAMINATION CHECK SHEET

1. B - THE VOLTAGE REGULATION OF A POWER SUPPLY IS PERFECT WHEN -- THE OUTPUT VOLTAGE REMAINS CONSTANT FROM ZERO LOAD CURRENT TO MAXIMUM LOAD CURRENT.
Selection B is desirable for current regulation. Selection C results in very poor regulation. Selection D is not possible under any circumstances.

2. D - THE PURPOSE OF A CURRENT REGULATOR IS TO -- MAINTAIN A CONSTANT LOAD CURRENT WITHIN SPECIFIED LIMITS OF LOAD RESISTANCE.
Selections B and C are accomplished by a voltage regulator; selection A represents an undesirable condition.

3. B - A ZENER DIODE IS VERY USEFUL BECAUSE -- ITS REVERSE VOLTAGE REMAINS NEARLY CONSTANT FOR VARIOUS VALUES OF REVERSE CURRENT.
Selection D is not a characteristic of a zener diode and its forward current characteristics are of little value.

4. A - IN FIGURE 7, D_1 IS CHANGED TO A ZENER DIODE THAT HAS A ZENER VOLTAGE OF 25.7 VOLTS. THE REMAINDER OF THE CIRCUITRY IS UNCHANGED. WHAT IS THE VALUE OF E_O? -- 25 VOLTS.
The value of E_O is the zener voltage minus the base-to-emitter voltage (0.7 volt) of the transistor. Therefore, $E_O = 25.7 - 0.7 = 25$ volts.

5. A - IN THE VOLTAGE REGULATOR OF FIGURE 9, -- Q_1 IS THE PASS TRANSISTOR AND Q_2 IS THE ERROR AMPLIFIER.
R_4 varies the output voltage from 20 to 30 volts, and D_1 supplies a reference voltage for the Q_2 emitter.

6. B - IN FIGURE 9, THE LOAD RESISTANCE IS CHANGED FROM 200 OHMS TO 100 OHMS. AS A RESULT -- THE Q_1 BASE CURRENT INCREASES.
The Q_2 collector current decreases, the regulated output voltage remains nearly constant, and the Q_2 emitter voltage remains nearly constant.

7. D - IN FIGURE 11, WHEN R_4 IS ADJUSTED TO INCREASE THE Q_2 BASE CURRENT, -- THE REGULATED OUTPUT VOLTAGE, E_O, DECREASES.
Concerning selections A, B and C, exactly opposite conditions are obtained.

8. B - IN FIGURE 15, A SMALL DECREASE IN E_O WILL CAUSE -- THE ON-TIME OF THE SWITCHING TRANSISTOR TO INCREASE.
The decrease in output voltage requires more energy from L_{11} so the on-time of the switch transistor must increase to supply this energy.

9. D - IN AN AUTOMATIC CROSSOVER SUPPLY, THE CIRCUIT OPERATES IN THE VOLTAGE REGULATING MODE -- WHEN THE LOAD RESISTANCE IS GREATER THAN THE CROSSOVER RESISTANCE.
When the load resistance is less than the crossover resistance, the circuit operates in the current regulating mode.

10. B - IN A PROPERLY FUNCTIONING CURRENT REGULATOR LIKE THAT OF FIGURE 18, WHEN THE LOAD RESISTANCE IS DECREASED -- THE OUTPUT VOLTAGE, E_O, DECREASES.
The load current remains nearly constant so the output voltage decreases.

QUESTIONS

IMPORTANT—These instructions **MUST** be accurately followed to avoid loss, or errors in grading.

Indicate your answer on this sheet by filling in the box for the most correct answer to each question, as illustrated in the example below.

When all questions have been answered, place the answer card in the proper position to line up the boxes on the card with the boxes on the sheet.

Next, copy the complete lesson code into the space provided on the card, and fill in the answer boxes to correspond with those previously filled in on this sheet.

Before mailing, be certain your correct student number, name and address appear on the card.

LESSON CODE
7410A

Example: A lighter-than-air craft that can be steered in flight is
A ☐ B ■ C ☐ D ☐
(A) an ornithopter. (B) a dirigible.
(C) a free balloon. (D) a helicopter.

1. A ☐ B ☒ C ☐ D ☐
The voltage regulation of a power supply is perfect when
(A) the dynamic internal impedance of the power supply is infinite. (B) the output voltage remains constant from zero load current to maximum load current. (C) the full-load output voltage is exactly half of the no-load output voltage. (D) the output voltage and current remain constant for all values of load resistance.

2. A ☐ B ☐ C ☐ D ☒
The purpose of a current regulator is to
(A) cause the load current to vary in direct proportion to the load resistance. (B) prevent changes in load voltage as the load current varies. (C) decrease the dynamic internal impedance of the power supply to a very low value. (D) maintain a constant load current within specified limits of load resistance.

3. A ☐ B ☒ C ☐ D ☐
A zener diode is very useful because
(A) its forward current remains constant as the forward voltage is increased. (B) its reverse voltage remains nearly constant for various values of reverse current. (C) its forward current increases linearly with forward voltage. (D) its reverse current varies directly proportional to reverse voltage.

4. A ☒ B ☐ C ☐ D ☐
In Figure 7, D is changed to a zener diode that has a zener voltage of 25.7 volts. The remainder of the circuitry is unchanged. What is the value of E_O?
(A) 25 volts. (B) 15 volts. (C) 20 volts. (D) 30 volts.

5. A ☒ B ☐ C ☐ D ☐
In the voltage regulator of Figure 9,
(A) Q_1 is the pass transistor and Q_2 is the error amplifier. (B) R_4 varies the output voltage from 25 to 50 volts. (C) Q_2 is the pass transistor and D_1 supplies the reference voltage. (D) Q_1 is the error amplifier and Q_2 supplies the reference voltage.

6. A ☐ B ☐ C ☐ D ☒
In Figure 9, the load resistance is changed from 200 ohms to 100 ohms. As a result
(A) the Q_2 emitter voltage increases. (B) the Q_1 base current increases. (C) the output voltage, E_O, increases. (D) the Q_2 collector current increases.

7. A ☒ B ☐ C ☐ D ☐
In Figure 11, when R_4 is adjusted to increase the Q_2 base current
(A) the Q_1 collector current increases. (B) the Q_3 emitter current increases. (C) the Q_2 collector voltage increases. (D) the regulated output voltage, E_O, decreases.

8. A ☐ B ☒ C ☐ D ☐
In Figure 15, a small decrease in E_O will cause
(A) the error signal voltage to increase. (B) the on-time of the switching transistor to increase. (C) the oscillation frequency to decrease. (D) the on-time of the switching transistor to decrease.

9. A ☐ B ☐ C ☐ D ☒
In an automatic crossover supply, the circuit operates in the voltage regulating mode
(A) for all values of load resistance. (B) when the load resistance is less than the crossover resistance. (C) when the load resistance is equal to the crossover resistance. (D) when the load resistance is greater than the crossover resistance.

10. A ☐ B ☒ C ☐ D ☐
In a properly functioning current regulator like that of Figure 18, when the load resistance is decreased
(A) the load current increases. (B) the output voltage, E_O, decreases. (C) the output voltage, E_O, increases. (D) the load current decreases.

PRACTICE EXERCISE SOLUTIONS (Continued)

40. E_O drops to zero.

41. The power must be turned off to deactivate the SCR, the cause of the overvoltage must be corrected, and the power then must be turned on again.

42. False—D_6 protects against reverse voltage.

43. 7.5 (the rated voltage of the zener diode)

44. Transistors Q_5 and Q_6 serve as a constant current source that develops a constant current through an external resistor for the reference voltage for the integrated circuit regulator.

45. differential

46. True

47. False—Resistor R_S is a current-sensing resistor which is used to sample the output load current.

48. True

QUESTIONS

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7410A

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(A) cause the load current to vary in direct proportion to the load resistance. (B) prevent changes in load voltage as the load current varies. (C) decrease the dynamic internal impedance of the power supply to a very low value. (D) maintain a constant load current within specified limits of load resistance.

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In the voltage regulator of Figure 9,
(A) Q_1 is the pass transistor and Q_2 is the error amplifier. (B) R_4 varies the output voltage from 25 to 50 volts. (C) Q_2 is the pass transistor and D_1 supplies the reference voltage. (D) Q_1 is the error amplifier and Q_2 supplies the reference voltage.

6. A ☐ B ☐ C ☐ D ☒
In Figure 9, the load resistance is changed from 200 ohms to 100 ohms. As a result
(A) the Q_2 emitter voltage increases. (B) the Q_1 base current increases. (C) the output voltage, E_O, increases. (D) the Q_2 collector current increases.

7. A ☒ B ☐ C ☐ D ☐
In Figure 11, when R_4 is adjusted to increase the Q_2 base current
(A) the Q_1 collector current increases. (B) the Q_3 emitter current increases. (C) the Q_2 collector voltage increases. (D) the regulated output voltage, E_O, decreases.

8. A ☐ B ☒ C ☐ D ☐
In Figure 15, a small decrease in E_O will cause
(A) the error signal voltage to increase. (B) the on-time of the switching transistor to increase. (C) the oscillation frequency to decrease. (D) the on-time of the switching transistor to decrease.

9. A ☐ B ☐ C ☐ D ☒
In an automatic crossover supply, the circuit operates in the voltage regulating mode
(A) for all values of load resistance. (B) when the load resistance is less than the crossover resistance. (C) when the load resistance is equal to the crossover resistance. (D) when the load resistance is greater than the crossover resistance.

10. A ☐ B ☒ C ☐ D ☐
In a properly functioning current regulator like that of Figure 18, when the load resistance is decreased
(A) the load current increases. (B) the output voltage, E_O, decreases. (C) the output voltage, E_O, increases. (D) the load current decreases.

PHOTOELECTRIC PRINCIPLES

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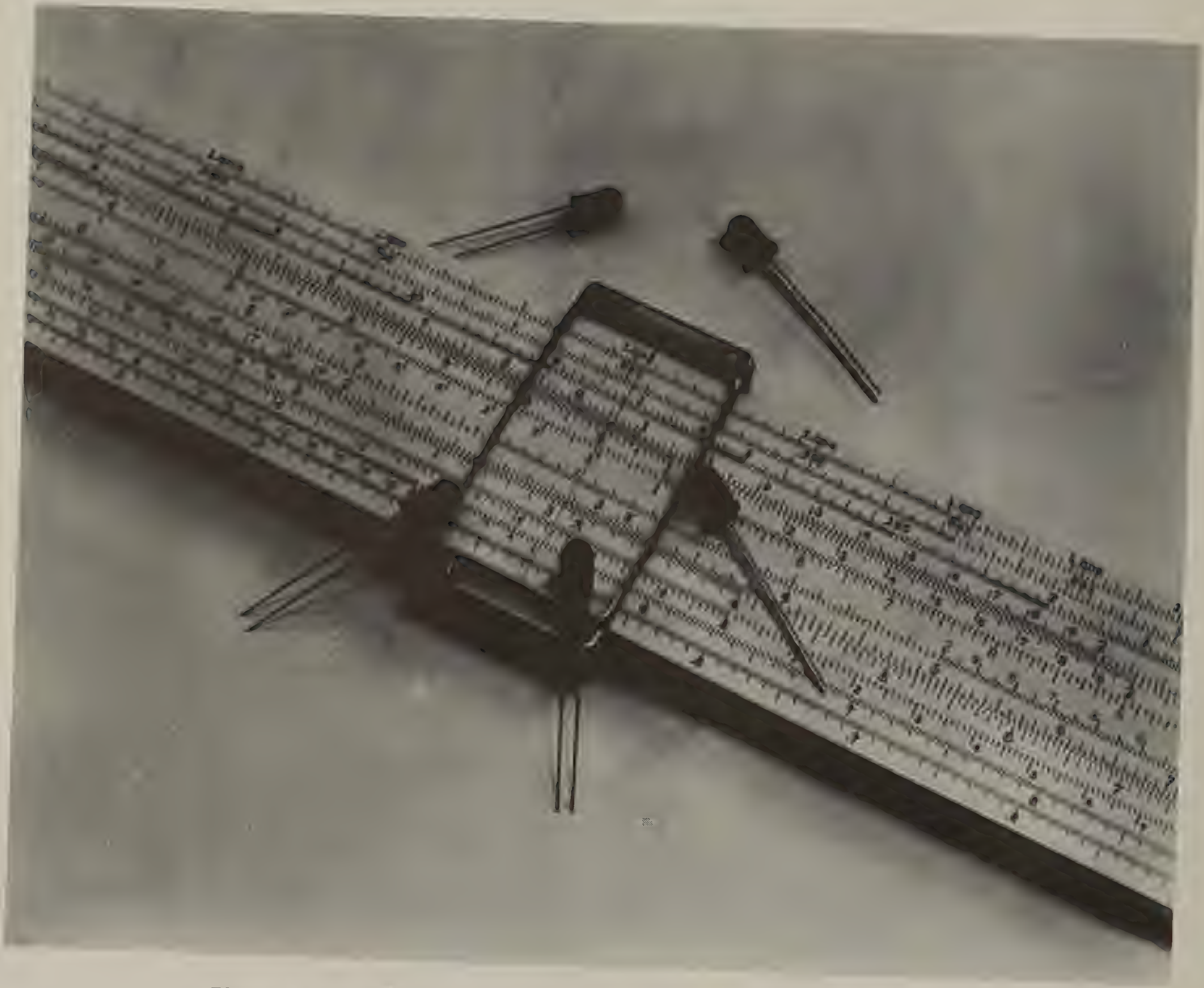

These 0.2 inch diameter red light-emitting diodes feature high-intensity illumination and flexible round leads for simple panel or PC board mounting. Devices such as these are rapidly replacing incandescent lamps in applications which require simple indicating devices.

Courtesy Monsanto Commercial Products Co.

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> *Failures are divided into two classes—those who thought and never did, and those who did and never thought.*
>
> *—John Charles Salak*

PHOTOELECTRIC PRINCIPLES

There are many uses for light energy in industry, in business and in the home. In industry, light energy is often used to count objects as they come off assembly lines or to determine if a jar or bottle is filled to the proper level as it comes out of a filling machine. Sorting objects according to size and color can also be accomplished with light energy. Light energy can even be used to control a furnace.

Other applications of light energy include burglar alarms in which an intruder breaks a beam of light and sets off a warning device. Many places of business use light-controlled annunciators which signal the storekeeper when a person enters. Light energy can even be used in a communications link by which voice signals can actually be transmitted on a beam of light.

In these and many other applications, the light energy is converted to another form of energy, usually electrical energy, or it is used to alter the characteristics of a device. The converted energy or change of characteristics of a device is then used to drive a counter, set off a burglar alarm or perform some other operation. The devices that convert light energy into other forms of energy or that change their characteristics with changes in light are usually called **PHOTOELECTRIC DEVICES**, although they may also be called **PHOTOELECTRIC CELLS**, or **PHOTOCELLS**.

Photoelectric devices may therefore be briefly described as those devices which are light sensitive or light controlled. In recent years however, devices have been developed which actually emit, rather than respond to, light. These relatively new light-emitting devices are almost within a class by themselves. The new light-emitting devices are now being used in many of the applications mentioned earlier as well as in new applications which have resulted from their discovery.

In this lesson the most commonly used photoelectric devices are described in detail. The photoelectric devices are arranged into groups according to their basic characteristics. The principle of operation behind each group is explained and then the individual devices are examined in detail. The lesson also covers the newer light-emitting devices as well as special devices which are made up of both light-sensitive and light-emitting devices. The lesson then concludes with some basic applications of some of the devices described.

UNITS OF LIGHT

Light is defined as radiant energy that may be perceived by the human eye. Most light comes from hot bodies such as the sun, burning fuels or incandescent lamps. However, light can also be produced by electrical and chemical means. Light, like other types of energy, can be measured and it can be used to perform many useful functions.

To effectively use light energy, we must be able to measure its important characteristics. We will therefore examine several basic units of measurement associated with light.

Some light sources produce a highly intense (extremely bright) light while other sources produce a light of low intensity or one which is very dim. A unit of measurement which is used to indicate the intensity of a light source is the **CANDLEPOWER**. In bygone days, one candlepower was equivalent to the light produced by a sperm candle $^7/_8$ of an inch in diameter, burning at a rate of 120 grains per hour. The more modern standard for the candlepower is a certain fraction of the average light intensity of a set of 45 carbon-filament lamps at the National Bureau of Standards. All other light sources are compared to this standard. Therefore, a light source which produces twice as much light as the standard is rated at 2 candlepower.

Light travels or flows outward from a source at a particular rate. The rate of flow or flux of visible radiation is commonly measured in units called **LUMENS**. Assume that a source of one candlepower is located at the center of a hollow spherical shell so that flux falls evenly on the entire inner surface of the shell. One lumen is the quantity of light falling on a fraction of the surface equal in area to r^2, where r is the radius of the shell. The total area of a spherical shell is $4\pi r^2$. As a result, the total flux emitted in all directions is 4π lumens.

Often it is desirable to measure the illumination or the amount of light flux falling on a unit area of a surface. The unit of measurement that is commonly used to measure illumination is the **FOOT-CANDLE**. One foot-candle is equal to one lumen distributed evenly over a surface area of one square foot.

The units of measurement just described are all directly related. The illumination in foot-candles can be determined by dividing the flux in lumens by the area in square feet. For example, if a source of one candlepower is located at the center of a hollow sphere whose radius is 1 foot, the illumination of the inner surface of the sphere would be equal to 4π lumens divided by 4π square feet, or 1 foot-candle.

Light energy can be measured in units other than those just described; however, the basic units just mentioned are easy to understand and are more than adequate for the discussions which follow.

PHOTOELECTRIC EFFECT

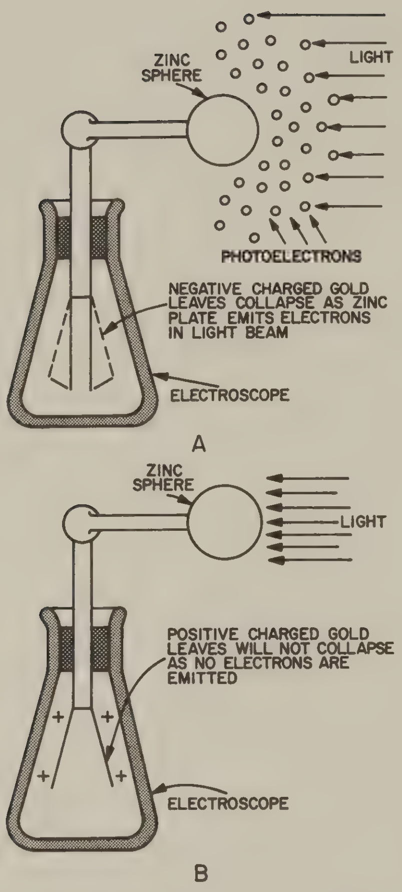

ZINC SPHERE
LIGHT
PHOTOELECTRONS
NEGATIVE CHARGED GOLD LEAVES COLLAPSE AS ZINC PLATE EMITS ELECTRONS IN LIGHT BEAM
ELECTROSCOPE
A
ZINC SPHERE
LIGHT
POSITIVE CHARGED GOLD LEAVES WILL NOT COLLAPSE AS NO ELECTRONS ARE EMITTED
+
+
+
+
ELECTROSCOPE
B

Figure 1

In the middle 1800's, it was found that if a clean zinc sphere, negatively charged, were connected to a gold leaf electroscope, it would lose its charge when ultraviolet light fell upon the sphere. Figures 1A and 1B illustrate this early experiment. In Figure 1A, when ultraviolet light falls on the negatively charged zinc sphere, the sphere emits electrons. These electrons are called **PHOTOELECTRONS,** and the action is referred to as the **PHOTOELECTRIC EFFECT.** The loss of electrons is indicated in the electroscope by the collapse of the gold leaves.

To carry the experiment a step further, the zinc sphere was then positively charged. When light fell upon the sphere, it was noticed that the positive charges were not emitted by the sphere. Therefore, light energy has an effect only on electrons.

The photoelectric effect previously described is the basic operating principle of many photoelectric devices. This effect is used to change light energy into electrical energy or to change the electrical characteristics of a photoelectric device.

Photons

In dealing with photoelectric devices, the concepts of light energy must be modified. Quite often, we think of light energy as being electromagnetic radiation. This wave concept of light energy cannot be used by itself to explain the photoelectric effect. Instead, light energy is thought of as consisting of little packets, or bundles, of energy called **PHOTONS**. The photons or bundles of light energy are thought of as being delivered by the light waves.

Spectral Sensitivity

Materials which exhibit photoelectric characteristics are usually more sensitive to light waves of one frequency. The color of light is determined by the frequency of the light waves. This characteristic of a photosensitive material is called its **SPECTRAL SENSITIVITY**. Different materials are used in photoelectric devices to make them sensitive to a particular frequency or color of light.

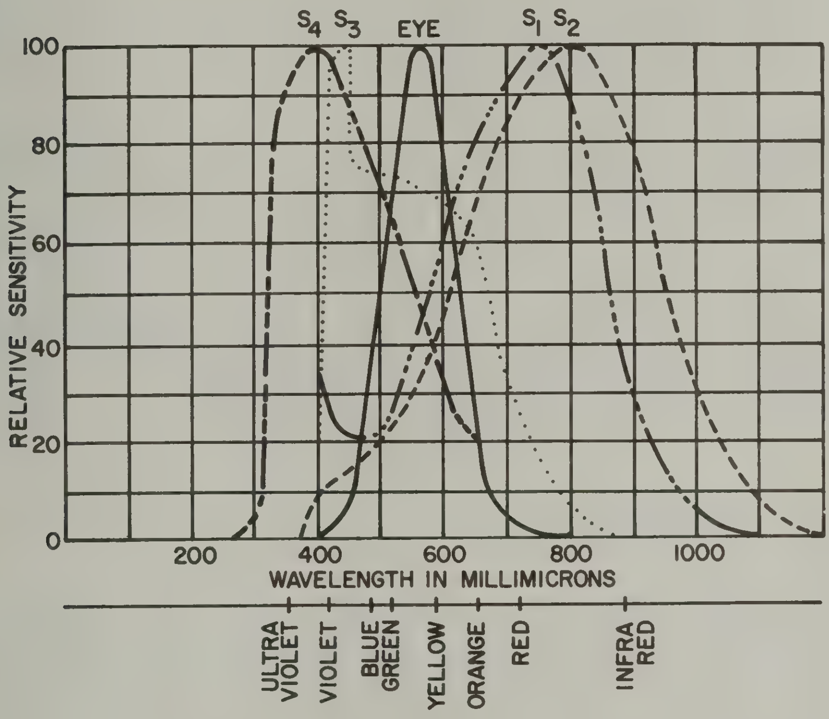


Figure 2

Figure 2 illustrates the sensitivity of a few types of photoelectric materials. For comparison, the spectral sensitivity of the human eye is shown. Notice that the human eye has its peak sensitivity in the green-yellow region. The other curves shown are labeled S_1, S_2, S_3 and S_4. The S_1 and S_2 materials have their peak sensitivity in the red and infrared regions. S_3 and S_4 are sensitive to colors from blue to ultraviolet.

S numbers are often used in rating photoelectric devices. For example, a photoelectric device with an S_1 spectral sensitivity has a peak response in the orange-red region. In other cases, the spectral sensitivity of a photoelectric device may be expressed as the wavelength at which its peak sensitivity occurs. For example, a photoelectric device may have a peak sensitivity at a wavelength of 800 millimicrons. Figure 2 shows that a wavelength of 800 millimicrons is in the red-infrared region.

PHOTOCONDUCTIVE DEVICES

In the photoelectric effect previously described, a photosensitive material was found to emit electrons when bombarded with light energy (photons). The energy of the emitted electrons is determined by the frequency of light energy. Increasing the intensity of the light energy does not increase the energy of the emitted electrons. Instead, it increases the number of electrons emitted from the materials.

The frequency at which the photoelectric effect occurs is called the **THRESHOLD FREQUENCY**. If the frequency of the light energy is reduced below the threshold frequency, electrons are not emitted from the material. However, it is found that below the threshold frequency the conductivity of the material is changed. When conductivity of a material is increased, the resistance of the material decreases. Thus, if light energy below the threshold frequency is applied to certain materials, their conductivity increases; that is, their resistance decreases. This action is referred to as the **PHOTOCONDUCTIVE EFFECT**.

Lead Sulphide Cells

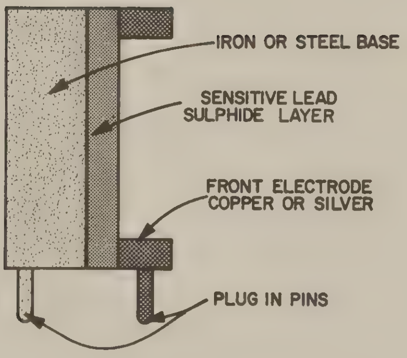

IRON OR STEEL BASE
SENSITIVE LEAD SULPHIDE LAYER
FRONT ELECTRODE COPPER OR SILVER
PLUG IN PINS

Figure 3

A device which exhibits the photoconductive effect is shown in Figure 3. This device is generally called a **LEAD SULPHIDE CELL**. The lead sulphide cell has an iron or steel base with a layer of lead sulphide applied to it. A copper or silver ring is placed on the front of the lead sulphide layer. Pins connected to both the front electrode and the iron or steel base provide an electrical connection to the lead sulphide layer.

With no light falling on the lead sulphide layer, the resistance of the lead sulphide layer is high. However, if light at a frequency to which lead sulphide is sensitive falls on the cell, the resistance of the lead sulphide layer decreases.

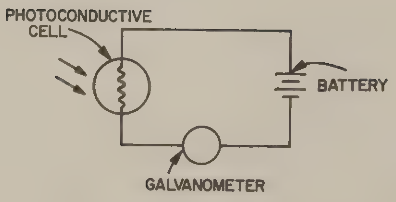


Figure 4

Figure 4 shows a symbol that is commonly used to represent a photoconductive cell in a basic photocell circuit. With no light on the cell in Figure 4, the resistance of the cell is high and circuit current is very low. However, when light falls on the sensitive lead sulphide layer, the internal resistance of the cell decreases and circuit current increases. A galvanometer (a very sensitive current meter) is used to measure the circuit current.

The current passed by a photoconductive cell when no light is falling on the cell (that is, when the cell is dark) is called the **DARK CURRENT**.

The resistance of the cell with no light falling on the cell is called the **DARK RESISTANCE**. Likewise, the resistance of the cell when illuminated is called the **LIGHT RESISTANCE** and the current produced at that time is called the **LIGHT CURRENT.**

The sensitivity of a photoconductive cell is usually given in milliamperes per foot-candle (mA/ft-candle) with a specified voltage across the cell. This sensitivity rating states how much current the cell can pass with a given illumination, and with a given voltage across the cell. For example, a particular cell has a sensitivity of 2.5 mA/1 ft-candle with 100 volts applied across the cell. This rating means that the cell can pass a current of 2.5 mA when 100 volts is applied across the cell and when it is illuminated by a 1 foot-candle light source.

Photoconductive cells are also rated according to their dark-to-light resistance ratio. This ratio expresses the change in cell resistance when light is applied. For example, a particular cell may have a dark resistance of 2.5 megohms. When 1 ft-candle of light is applied, the cell resistance drops to 2500 ohms. The dark-to-light resistance ratio is thus:

$$\frac{2,500,000}{2500} = 1000.$$

Cadmium Sulphide and Cadmium Selenide Cells

Two photoconductive cells which are widely used in electronic equipment are the **CADMIUM SULPHIDE** and **CADMIUM SELENIDE CELLS**. The basic construction of these cells is shown in Figure 5A. The cells consist of a ceramic or glass base with a layer of cadmium sulphide or cadmium selenide. Indium contacts are placed at each end of the cadmium sulphide or selenide layer. These contacts provide an electrical connection to the layer.

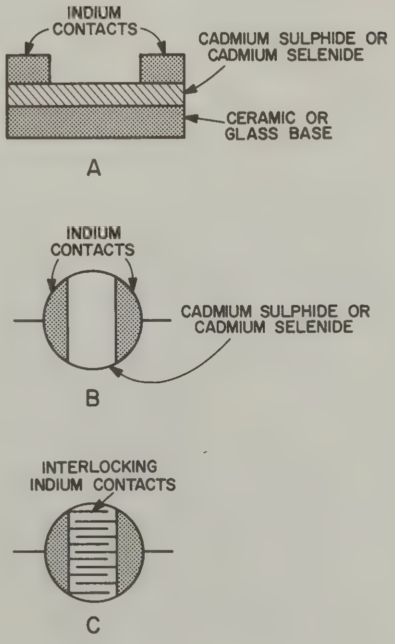
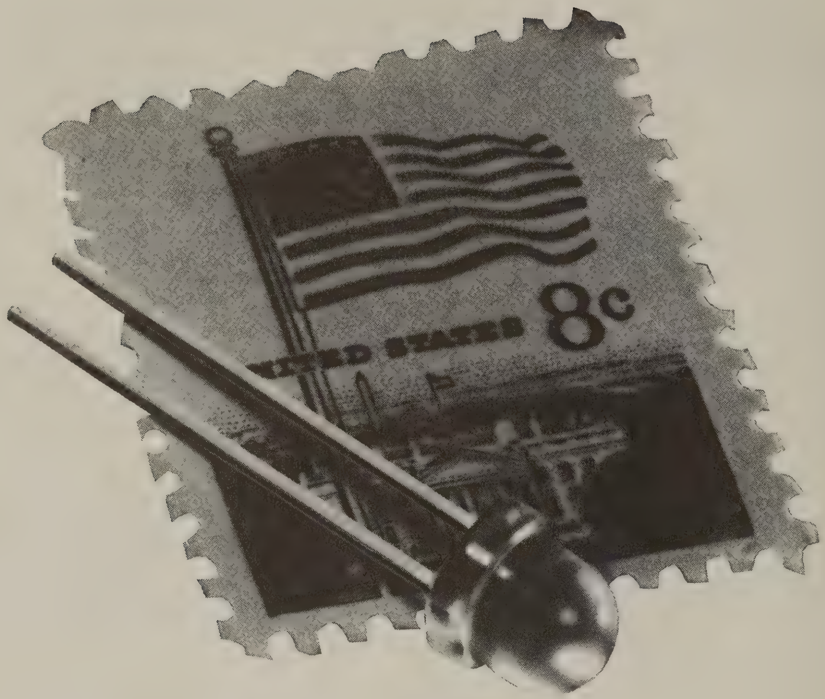

INDIUM CONTACTS
CADMIUM SULPHIDE OR CADMIUM SELENIDE
CERAMIC OR GLASS BASE
A
INDIUM CONTACTS
CADMIUM SULPHIDE OR CADMIUM SELENIDE
B
INTERLOCKING INDIUM CONTACTS
C

Figure 5

Figure 5B shows a top view of the cell. The cell shown is circular with the indium contacts at each end; however, other configurations can also be used. With no light falling on the cell, the resistance of the cadmium sulphide or selenide layer is high. Thus, the resistance between the indium contacts is high. However, when light falls on the cell, the resistance of the layer decreases, thus decreasing the resistance between the indium contacts.

To decrease the light resistance of the cadmium sulphide or cadmium selenide cells, the indium contacts can be arranged in an interlocking arrangement, as shown in Figure 5C. Each set of interlocking contacts becomes a small resistor in parallel with the others. The interlocking



The relative size of a typical light-emitting diode becomes apparent when it is compared to a postage stamp as shown above.

Courtesy Genesco Technology Corporation

contact arrangement also increases the sensitivity of the cell. That is, the light intensity required to develop a particular current is decreased when the interlocking contact arrangement is used.

Cadmium sulphide and cadmium selenide cells are very popular. These devices are highly sensitive and they may be operated at either high or low voltages. They are commonly used in devices such as cameras, electronic tachometers, electronic intrusion alarms and many other devices which are light controlled. In general, the cadmium selenide cells are more sensitive than the cadmium sulphide cells. The response time of a cadmium selenide cell is also shorter than that of a cadmium sulphide cell. The response time of a photoconductive cell is simply the time required for the cell's resistance to drop to its light resistance value after light is applied to the cell.

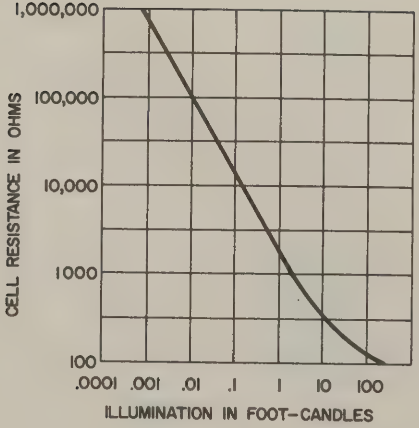


Figure 6

Figure 6 shows the characteristics of a typical cadmium sulphide cell. At low levels of illumination, the cell has a resistance of about 1,000,000 ohms (1 megohm). As the illumination increases to about 100 foot-candles, the resistance of the cell decreases to about 100 ohms. Depending on the actual construction of each type of cell, these characteristics can be varied to fit the application.

The following Practice Exercise questions cover the subjects which you have just studied. They are:

UNITS OF LIGHT

PHOTOELECTRIC EFFECT

- PHOTONS
- SPECTRAL SENSITIVITY

PHOTOCONDUCTIVE DEVICES

- LEAD SULPHIDE CELLS
- CADMIUM SULPHIDE AND CADMIUM SELENIDE CELLS

1. What is a lumen?
2. What is a foot-candle?
3. What are photoelectrons?
4. What are photons?
5. The ability of a material to respond to a particular frequency of light is called its (a) candlepower, (b) spectral sensitivity, (c) maximum current rating.
6. An S_1 material has its peak sensitivity in the ________________________ region.
7. The frequency at which the photoelectric effect occurs is called the ____________________ frequency.
8. The photoconductive effect causes the resistance of a material to ________________ when light falls on the material.
9. The lead sulphide, cadmium sulphide and cadmium selenide cells are photoconductive cells. True or False?
10. The current passed by a photoconductive cell when no light is falling on the cell is called __________ current.
11. What is meant by the term "light resistance?"

12. If a photoelectric cell has a dark resistance of 1.5 megohms and a light resistance of 2000 ohms, the cell has a dark-to-light resistance ratio of (a) 1000, (b) 750, (c) 7500, (d) 1750.

13. The use of interlocking contacts in the photoconductive cell of Figure 5C increases its light resistance. True or False?

PHOTOVOLTAIC DEVICES

The photoelectric effect illustrated in Figures 1A and 1B shows that zinc emits electrons when bombarded with light energy. Because the zinc gives up electrons, it becomes positively charged. This same principle is used in photoelectric devices that develop a voltage when illuminated. A device of this type is called a **PHOTOVOLTAIC DEVICE**. A photovoltaic device requires no external power supply like the photoconductive devices previously described. The output voltage developed by a photovoltaic device is often used to operate a relay or some other device.

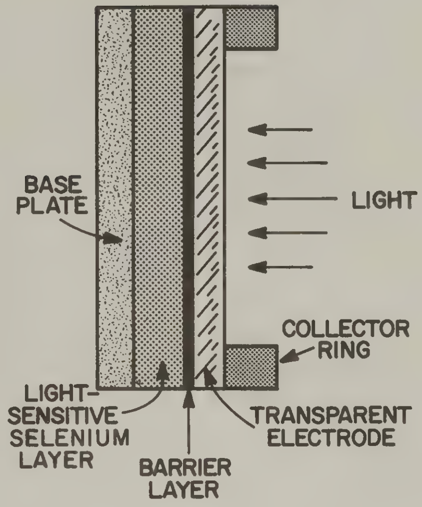


Figure 7

Selenium Photocells

Figure 7 shows a cross-sectional view of a **SELENIUM PHOTOVOLTAIC CELL**. The light-sensitive material in this cell is a layer of selenium on a base plate. A barrier layer is placed over the selenium layer. Next, a transparent conductive electrode is placed over the barrier layer. The collector ring provides an electrical connection to the conductive layer. The output voltage developed by this cell appears between the base plate and the collector ring. A photovoltaic cell of this type is shown in Figure 8.

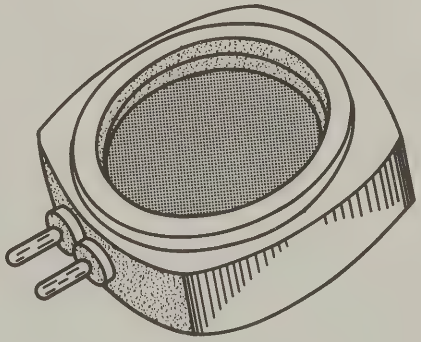


Figure 8

In operation, light energy passes through the transparent electrode and strikes the light-sensitive selenium layer. The photoelectrons emitted by the selenium layer pass through the thin barrier layer and are collected by the transparent electrode. The barrier layer prevents the photoelectrons from returning to the selenium layer. The barrier layer is usually selenium oxide. This barrier layer, together with the selenium layer, combine to act like a diode, permitting electron flow in only one direction—from the selenium layer to the transparent electrode.

Because the selenium layer emits photoelectrons, it has a deficiency of electrons. The transparent electrode, because it collects the photoelectrons, has an excess of electrons. Thus, the selenium layer and the base plate are positively charged, while the transparent electrode is negatively charged. This difference in charge forms a difference of potential between the base plate and the collector ring.

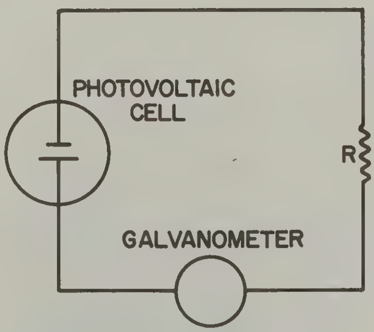


Figure 9

The standard symbol for a photovoltaic cell is shown in the basic circuit of Figure 9. With no light, there is no output voltage developed by the photovoltaic cell, and circuit current is zero. However, when light is present, the photovoltaic cell develops an output voltage. The galvanometer is used to measure the circuit current.

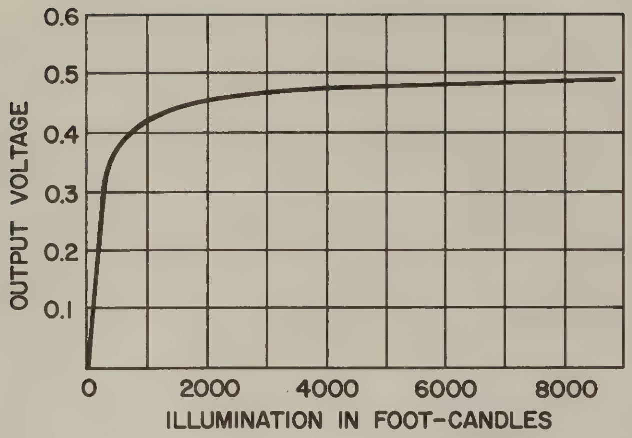


Figure 10

Figure 10 shows the characteristics of a typical photovoltaic cell. Notice that the output rises rapidly as the illumination increases from 0 to 1000 foot-candles. Increasing the illumination above 1000 foot-candles does not increase the output voltage appreciably. As indicated in Figure 10, the maximum output voltage developed by the photovoltaic cell is a little less than half a volt (0.5 volt). Higher output voltages can be obtained by connecting the photovoltaic cells in series. The current supplied by a single cell is also quite small. Higher currents can be obtained by connecting the photovoltaic cells in parallel.

Photovoltaic cells are sometimes referred to as solar cells, or sun batteries. The reason they are placed in the class of cells or batteries is that the output voltage they develop can be used to operate electronic equipment. In these applications, the sun's rays are used to energize the photovoltaic cells. The photovoltaic cell is one means of converting the sun's rays into electrical energy. The solar cells are used to supply power to artifical satellites that circle the earth.

Silicon Photocells

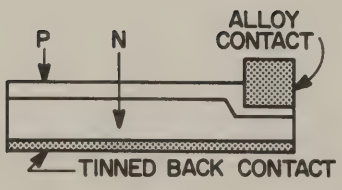


Figure 11

Photovoltaic cells are also constructed from silicon material. Figure 11 shows a cross section of a **SILICON PHOTOVOLTAIC CELL**. The cell consists of two doped semiconductor materials forming a PN junction. The N-type semiconductor material is a piece of properly doped silicon. The P-type layer is formed by diffusing boron on the surface of the N-type material. An aluminum layer is bonded to the P-type layer, and a contact is alloyed to this aluminum layer. An electrical connection is made to the N-type silicon material by tinning the back of the silicon material. The contact to the P-type material is the positive terminal of the cell, and the contact to the N-type material is the negative terminal.

The PN junction in the photovoltaic cell of Figure 11 is exactly like the PN junction in a transistor. In the immediate area of the PN junction, no free electrons are present in the N-type material and no holes are present in the P-type material. This region around the PN junction is called the depletion region. When the photovoltaic cell of Figure 11 is illuminated, photons that reach the PN junction generate hole-electron pairs in the depletion region. The holes diffuse into the P-type material, and the electrons diffuse into the N-type material. The N-type material thus has an excess of electrons and is negatively charged, while the P-type material has an excess of holes and is positively charged. This difference in charge produces a difference in potential. Connecting an external circuit to the PN junction develops a current in the external circuit whenever light falls on the PN junction.

PHOTODIODES

Besides being used as a photovoltaic cell, the silicon device of Figure 11 can also be used as a PHOTODIODE. In this application, the PN junction is reverse biased by an external voltage source. With no light falling on the PN junction, only a small reverse current, or dark current, exists. This small reverse current is basically a leakage current which results from thermal generation of hole-electron pairs. The small number of electrons that diffuse into the N-type material is attracted toward positive potential applied to the N-type material, while the small number of holes created in the P-type material allows electrons to enter the P-type material from the negative side of the power source. This results in a very small electron flow through the photodiode. However, when light strikes the PN junction, the reverse current increases in proportion to the intensity of the light falling on the junction. This action occurs because the photons reaching the PN junction create additional hole-electron pairs. This increases the conductivity of the photodiode, producing additional current.

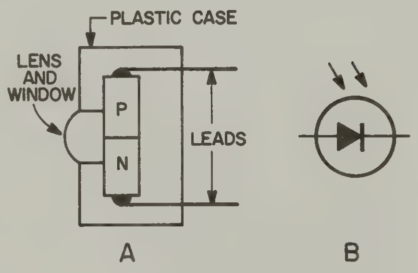


Figure 12

Photodiodes are often constructed as shown in Figure 12A and represented by the symbol shown in Figure 12B. The PN junction is enclosed in a plastic case as shown, which has a window and lens assembly that focuses light on the PN junction. Figure 13 shows a basic photodiode circuit, where battery B_1 reverse biases the photodiode, and the galvanometer is used to measure the current in the circuit. With no light falling on the photodiode PN junction, only a small reverse current exists in the circuit. However, when light falls on the photodiode PN junction, the reverse current increases.

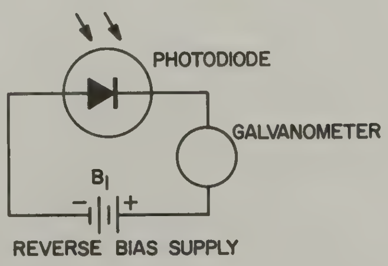


Figure 13

The characteristic curve shown in Figure 14 indicates the relationship between photodiode current and illumination. The relative values shown were recorded while the reverse-bias voltage was held constant at 3 volts. Notice that the photodiode current increases in direct proportion with

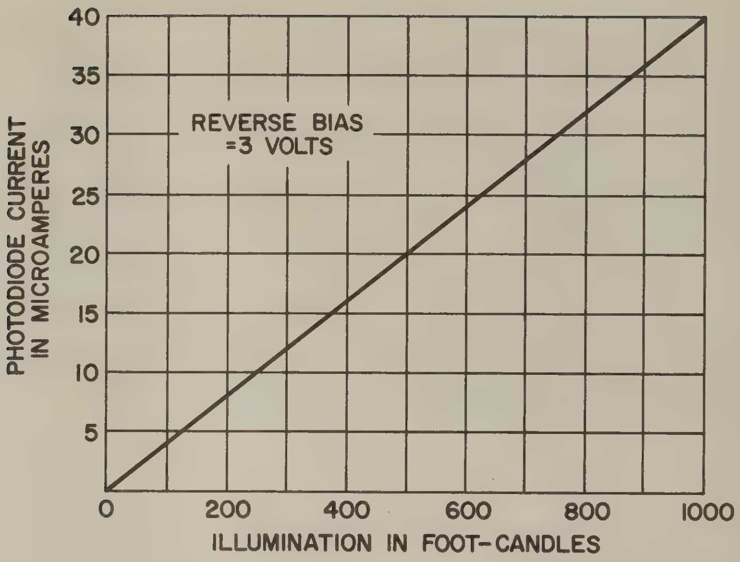


Figure 14

illumination. When the illumination reaches a value of 1000 foot-candles, the photodiode current reaches a value of 40 microamperes. A further increase in illumination would cause a continued increase in current; however, the photodiode could be damaged due to excessive current. Therefore, precautions are usually taken to insure that excessive current (caused by excessive illumination) is not produced when the photodiode is used in a particular application.

Although Figure 14 indicates that the photodiode current essentially drops to zero when the illumination drops to zero, an extremely small current still exists across the photodiode PN junction. As previously mentioned, a leakage current (also called a dark current) exists even when no light strikes the photodiode. The particular photodiode represented by Figure 12 has a typical dark current of less than 1 nanoampere (1×10^{-9} ampere).

Photodiodes have a much faster response than the photoconductive cells previously described. In other words, photodiodes will respond much faster to changes in light intensity. Photodiodes are therefore commonly used in linear and digital (switching) applications where speed (a fast response) is important.

In addition to the typical photodiode just described, other photodiodes are also available which have specific advantages over this typical photodiode. For example, ultrafast photodiodes are created by altering the basic photodiode construction. These ultrafast photodiodes are often as much as 100 times faster than the typical photodiodes.

Another type of photodiode which is available is the avalanche photodiode. The avalanche photodiode is operated with a reverse-bias voltage that is near the avalanche or breakdown voltage of the photodiode. When the reverse-bias voltage approaches the level of the breakdown voltage, hole-electron pairs are created as photons strike the PN junction of the photodiode. However, these hole-electron pairs acquire sufficient energy to create additional hole-electron pairs by colliding with other substrate atoms. A multiplication effect is therefore produced, and the resulting current is much higher than that of a typical photodiode. The avalanche photodiode is therefore more sensitive than the typical photodiode previously described.

PHOTOTRANSISTORS

As previously mentioned, the output voltage developed by a photovoltaic cell is quite low. The output from a single cell will not always be large enough to operate a relay or some other load device. As a result, amplification is often required. A similar situation occurs when photoconductive devices are used or when some types of photodiodes are used. A device which overcomes this disadvantage is the **PHOTOTRANSISTOR**. The phototransistor acts like a photodiode and a transistor amplifier all in one unit.

If an additional PN junction were added to the photodiode shown in Figure 13, the device would effectively become a phototransistor. A phototransistor is therefore a three-layer semiconductor device quite similar to a conventional transistor. However, unlike the conventional transistor which responds to changes in input current, the phototransistor responds to changes in light intensity.

The operation of an NPN phototransistor is shown in Figure 15. Notice that no connection is made to the base of the phototransistor. Instead, a lens is used to focus light on the emitter-base and collector-base junctions of the phototransistor. Also, notice that the NPN phototransistor is biased in the same manner as a conventional NPN transistor; the external battery (B_1) is connected so that the emitter is negative with respect to the collector.

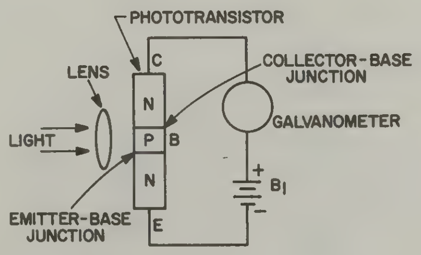


Figure 15

When light strikes the phototransistor shown in Figure 15, hole-electron pairs are generated within the vicinity of the collector-base junction. The holes tend to gather in the base region and the electrons tend to accumulate in the collector region. However, a charge will not accumulate across the junction because the holes and electrons disperse throughout the base and collector regions. Some of the holes diffuse across the base region toward the emitter-base junction. When they reach the emitter-base junction, they are injected into the emitter. This, in turn, causes the emitter to inject electrons into the base region. However, the number of electrons injected into the base greatly exceeds the number of holes entering the emitter. This occurs because the emitter injection efficiency is much higher than the base injection efficiency. The final result is simply that the electrons injected by the emitter travel across the base and are drawn into the collector. These electrons then combine with the electrons that were originally generated at the collector-base junction and appear as collector current.

The amount of current through the phototransistor shown in Figure 15 is therefore ~~determined by the intensity of the applied light~~. For a given light intensity, the phototransistor ~~passes a much~~ greater current than a photodiode. To illustrate this fact, the characteristics of a typical phototransistor are shown in Figure 16. Notice that the current through the phototransistor increases proportionally with illumination. When the illumination is equal to 1000 foot-candles, the phototransistor current is equal to 10 milliamperes. This, of course, is a much higher current than could be obtained with the photodiode previously described.

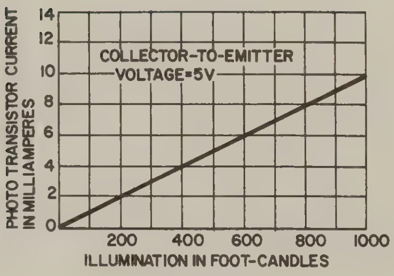


Figure 16

Although Figure 16 appears to indicate that the current through the phototransistor drops to zero when illumination drops to zero, a small current (dark current) still is present. This dark current is usually in the nanoampere or low microampere range.

Phototransistors are constructed in basically the same manner as photodiodes. However, phototransistors may be constructed with either two or three leads. In the three-lead type, the base is made electrically available, and the device may be used as a conventional transistor as well as a phototransistor. There are also some applications where the phototransistor is used as a phototransistor, but the base lead is used to connect the bias voltage for an optimum operating point. In most applications however, only two leads are required (emitter and collector) and the phototransistor is used in much the same manner as a photodiode.

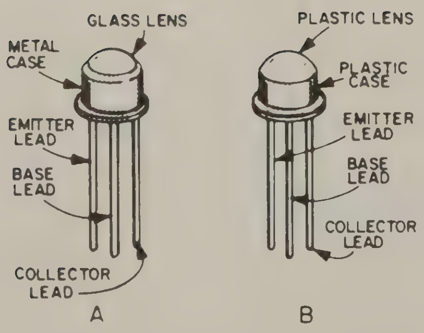


Figure 17

A typical three-lead phototransistor is shown in Figure 17A. The actual phototransistor circuit (also called a chip) is mounted inside of the metal case. A glass lens is then hermetically sealed to the case to keep out moisture. This lens collects any applied light and focuses it on the chip. The three leads are connected to the emitter, base and collector regions of the phototransistor. A similar phototransistor is shown in Figure 17B. This phototransistor also has three leads but the lens and case are made of special plastic materials which are capable of resisting heat and moisture. The photodiodes previously described may also appear as shown in Figures 17A and 17B. However, in the construction of a photodiode, only two leads are required for connection to the cathode and anode.

In general, phototransistors provide a greater output current than photodiodes because they actually provide amplification. However, phototransistors do not respond as quickly to changes in light intensity. Both photodiodes and phototransistors are usually made of silicon, although germanium is used for special applications. Silicon devices usually provide better performance characteristics. They are highly reliable and are sensitive throughout the visible and near-infrared portions of the light spectrum; therefore, they are ideally suited for applications where the applied light is obtained from incandescent lamps.

The symbol commonly used to represent the phototransistor is shown in Figure 18. The base lead is not shown because it is seldom used. However, in special applications where the base lead is required, it is also appropriately indicated on the symbol.

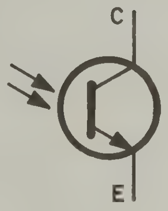


Figure 18

The phototransistor is much more sensitive to light than a photodiode. However, it is possible to obtain even greater sensitivity by connecting two phototransistors together as shown in Figure 19. The two phototransistors shown are connected in a Darlington arrangement so that the signal amplified by the first transistor is amplified again by the second transistor. This type of circuit is commonly referred to as a **PHOTO DARLINGTON AMPLIFIER** and it offers the same advantages as a Darlington circuit which uses conventional transistors.

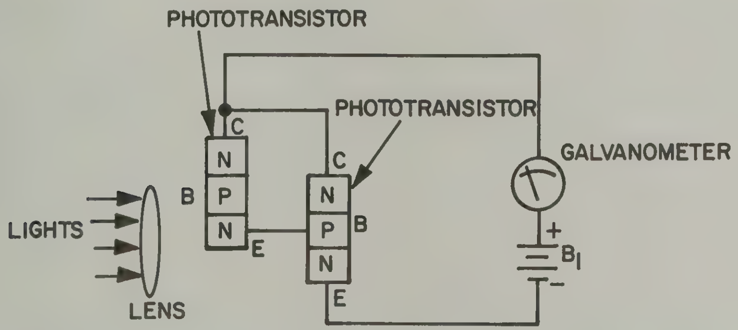


Figure 19

The overall current gain of the photo Darlington amplifier is equal to the current gain of the first phototransistor multiplied by the current gain of the second phototransistor. For example, if the first phototransistor has a current gain (also called beta) of 40 and the second phototransistor has a current gain of 40, the overall gain of the Darlington amplifier would be equal to 40 times 40, or 1600. This, of course, is a much higher gain than could be obtained from a single phototransistor. The first phototransistor actually behaves as if it were a variable resistance connected in the base circuit of the second phototransistor. The base current of the first phototransistor is controlled by the light, and this phototransistor, in turn, controls the base current of the second phototransistor.

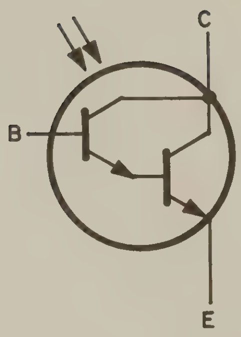


Figure 20

The photo Darlington amplifier is constructed by mounting both phototransistors in a sealed case which has an appropriate window, or lens system. Light is usually applied to both phototransistors, as shown in Figure 19. The photo Darlington amplifier usually has three leads (emitter, base and collector) and resembles a three-lead phototransistor in appearance. As with phototransistors, the base lead can be used to connect the bias voltage to the device at an optimum operating point or it can be left disconnected. A symbol commonly used to represent a photo Darlington amplifier is shown in Figure 20. The base lead may be as illustrated in Figure 20 or it may be omitted, depending upon the application.

The high gain provided by the photo Darlington amplifier makes it suitable for many applications where maximum sensitivity is required. Unfortunately, the photo Darlington amplifier ranks among the slowest of the junction photo devices; therefore, it cannot be used in applications where light intensity changes at an extremely fast rate.

PHOTO SCR'S

Photodiodes and phototransistors respond well to changing light intensities and produce output currents which are proportional to the applied light at any instant of time. They may also be used as simple on-off switches where they are required to conduct or turn on when light is applied to them and effectively stop conducting or turn off when light is removed from them. However, when these devices are used as switches, they are capable of supplying relatively small currents and therefore provide limited power control.

Occasionally, photodiodes and phototransistors are used to operate sensitive electromechanical relays which, in turn, may be used to control large amounts of power. However, the relays themselves have disadvantages when used to control large currents or voltages. There is, however, a light-controlled device which is capable of directly controlling relatively high currents and voltages. This light-controlled device is commonly referred to as a **PHOTO SCR** (photo silicon control rectifier) or a **LIGHT ACTIVATED SCR** (abbreviated LASCR).

The photo SCR may be referred to as the switching member of the photo-device family. The photo SCR has the same basic characteristics as a conventional SCR except it is activated by light instead of an input voltage.

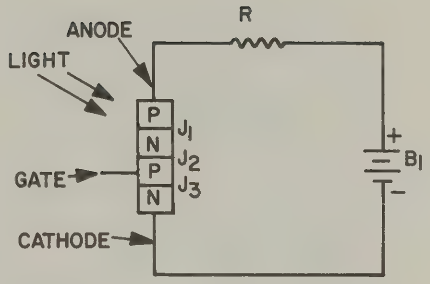


Figure 21

The basic construction of a photo SCR is shown in Figure 21. The photo SCR has three junctions (labeled J_1, J_2 and J_3) just like a conventional SCR, and it is biased in the same manner. When the proper operating voltage is applied (as shown in Figure 21), junctions J_1 and J_3 become biased and junction J_2 becomes reverse biased. As long as no light is applied to the photo SCR, only a small (negligible) leakage current will exist through junction J_2. However, when a small amount of light is applied to the photo SCR, hole-electron pairs are generated in the vicinity of junction J_2, and a small but noticeable current occurs through the junction. If the intensity of the applied light continues to increase, the current through junction J_2 will also increase, and a point is eventually reached where the junction will break down, allowing a much higher current through the photo SCR. The photo SCR effectively acts as a short at this time, and the circuit current is essentially controlled by the external load resistor (R) shown in Figure 21.

Like the conventional SCR, the photo SCR is either off (conducting an extremely small current) or on (conducting heavily). The photo SCR effectively turns on when the intensity of the applied light reaches a specific point. Once the photo SCR turns on, it remains on even if the light intensity drops to zero. As with the conventional SCR, the photo SCR can be turned off only by reducing the current through it below its particular holding current. The photo SCR then turns off and effectively blocks any current.

The amount of light required to turn on, or trigger, a photo SCR is dependent upon such factors as the operating voltage, the junction temperature and the amount of gate-to-cathode resistance. In general, the amount of light required to trigger a photo SCR becomes less as the operating voltage increases. The same is also true as the junction temperature increases. To obtain optimum sensitivity, the photo SCR is usually constructed of a very thin silicon pellet so that it can be triggered by very small light-induced currents.

The sensitivity of a photo SCR can be effectively controlled by varying its gate-to-cathode resistance. In other words, a resistor can be connected between the gate and cathode of the photo SCR to control the point at which it will trigger. The gate-to-cathode resistor effectively bypasses current around the gate-cathode junction (J_3 in Figure 21), reducing the sensitivity of the photo SCR. A high value of resistance (typically 20 to 60K ohms) is generally used when high sensitivity is required, and a low value of resistance (often less than 4K ohms) is used when the sensitivity of the photo SCR must be lowered.

Because photo SCR's are constructed for optimum sensitivity, they are not suitable for controlling very high currents. However, they are capable of ~~handling much higher~~ currents than photodiodes or phototransistors. Presently used photo SCR's are capable of switching currents of 1 or 2 amperes and withstanding operating voltages as high as 200 volts.

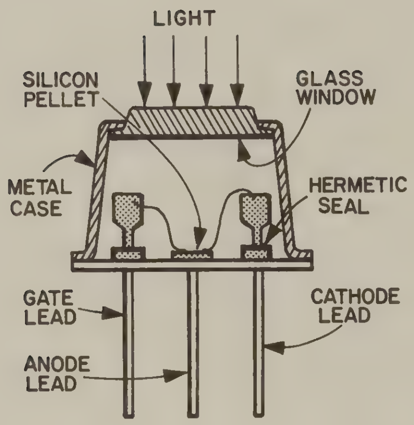


Figure 22

A cross-sectional view of a typical photo SCR is shown in Figure 22 to emphasize the relative location of each part. Notice that the silicon pellet (chip) is mounted on the base of the metal case directly below the glass window so that it will receive the maximum amount of incoming light. The gate and cathode leads are brought through the bottom of the case and hermetically sealed to prevent moisture from entering the case. The leads are connected to the appropriate regions of the silicon pellet with very thin wires. The anode lead connects directly to the case which makes electrical contact with the anode region of the silicon pellet.

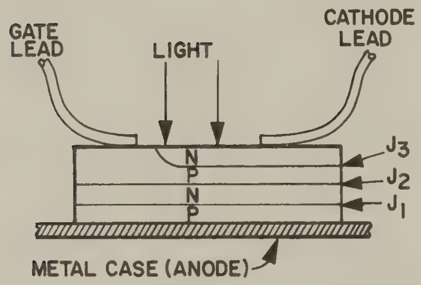


Figure 23

A detailed view of the silicon pellet is shown in Figure 23. The pellet is mounted so that the lower anode region makes electrical contact with the metal case as shown. Each region or layer is extremely thin so that maximum sensitivity to light can be obtained. The gate and cathode leads are connected directly to the gate and cathode regions at the top of the pellet. Junctions J_1, J_2 and J_3 correspond to the same junctions shown in Figure 21.

The symbol most commonly used to represent the photo SCR is shown in Figure 24. This symbol is almost identical to the conventional SCR symbol.

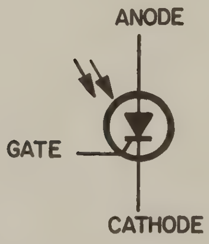


Figure 24

SOLID-STATE EMITTERS

Incandescent lamps have been used for many years to produce light for a variety of purposes. They may be used to simply provide house lighting or they may be used in complex electronic equipment to indicate when various circuits are functioning. Other devices, such as neon lamps and neon-glow tubes, have also been used to provide indications which relate to equipment operation. However, all of these devices have certain disadvantages which make them unsuitable for use in modern transistorized electronic equipment. When used in electronic equipment, incandescent lamps have a limited life expectancy and require considerable current for operation. Both of these factors make them unsuitable for use in transistorized equipment which is designed for long life and minimum power consumption. Neon devices require little current and offer an extended life expectancy; however, they require a ~~relatively high~~ voltage (typically 90 volts dc or higher) for operation. Because most transistorized equipment operates at relatively low voltages (typically 5 to 20 volts dc), sufficient voltage is usually not available for neon devices.

The following Practice Exercise questions cover the subjects which you have just studied. They are:

PHOTOVOLTAIC DEVICES
  SELENIUM PHOTOCELLS
  SILICON PHOTOCELLS
PHOTODIODES
PHOTOTRANSISTORS
PHOTO SCR'S

14. Photoelectrons are emitted by the barrier layer in the photovoltaic cell of Figure 7. True or False?

15. For the photovoltaic cell of Figure 9, an increase in light intensity causes (a) an increase in the output voltage, (b) a decrease in the output voltage.

16. When light falls on the PN junction of the photovoltaic cell of Figure 11, hole-electron pairs are formed in the immediate area of the junction. True or False?

17. In the photodiode circuit of Figure 13, an increase in light intensity causes (a) a decrease in reverse current, (b) an increase in reverse current.

18. For a given light intensity, a phototransistor will pass (a) more current than a photodiode, (b) less current than a photodiode.

19. Phototransistors are always constructed with two leads. True or False?

20. The photo Darlington amplifier is a special type of (a) photo SCR, (b) phototransistor, (c) photodiode.

21. The photo Darlington amplifier provides low gain but has a very fast response time. True or False?

22. Photo SCR's are capable of controlling more power than phototransistors. True or False?

23. An effective means of varying the sensitivity of a photo SCR is by changing the value of its (a) gate-to-anode resistance, (b) gate-to-cathode resistance, (c) cathode-to-anode resistance.

24. The photo SCR turns on when light is applied and turns off when the light is removed. True or False?

The need for a more efficient light source, suitable for use with both permanent and portable transistorized electronic equipment, led to the development of a solid-state light-emitting device known as the **LIGHT-EMITTING DIODE (LED)**. The LED is rapidly becoming one of the most popular indicating devices for use in modern electronic equipment. Because the LED is constructed of semiconductor materials, it is virtually immune to failure or mechanical breakdown. It also operates at very low voltages and currents which can be easily obtained from most transistorized equipment.

The LED is basically a PN junction diode that emits light when it is forward biased. The wavelength or color of the light produced is determined primarily by the type of materials used to form the PN junction. The LED works on the principle that photons of light energy can be produced when certain semiconductor materials are excited in a manner which allows recombination of holes and electrons.

The basic construction of an LED is shown in Figure 25. The LED shown utilizes flat, or planar, construction in which a shallow P-type layer is diffused into an N-type substrate, and the entire structure is mounted on a metal base, or header. If the resulting PN junction is forward biased as shown, electrons in the N-type layer are injected into the P-type layer where they combine with excess holes. As each hole and electron combine, a photon of light is generated. Most of the generated photons travel through the semiconductor material and escape the surface as light; however, some of the photons are reabsorbed. The wavelength or color of the light is determined by the type of semiconductor material used. Materials such as gallium phosphide (GaP) and gallium arsenide phosphide (GaAsP) are commonly used to produce visible light (green and red, respectively), while gallium arsenide (GaAs) is often used to produce light in the near-infrared region. Although other types of materials can be used to produce additional colors, the three types of materials just mentioned are presently the most practical and therefore the most popular materials being used.

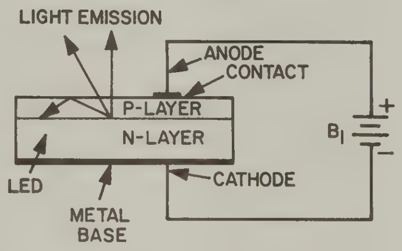


Figure 25

Most of the light emitted by an LED is produced at the PN junction. Also, the intensity of the light is quite low when compared with even a very small incandescent lamp. Therefore, it is necessary to construct the LED in a way which will allow it to emit the maximum amount of light possible. The basic planar, or flat-geometry, LED shown in Figure 25 is not efficient in this respect. The photons which leave the PN junction and travel directly toward the surface, or at a small angle with respect to the surface, are allowed to escape. However, photons which strike the surface at, or greater than, a specific angle are reflected back into the material and reabsorbed. The exact angle at which reflection occurs is referred to as the **CRITICAL ANGLE**; it varies from one type of semiconductor material to the next. For example, gallium arsenide has a very low critical angle of approximately 16°. This means that all photons that strike the surface of the gallium arsenide material at an angle greater than 16° will be reflected internally. Therefore,

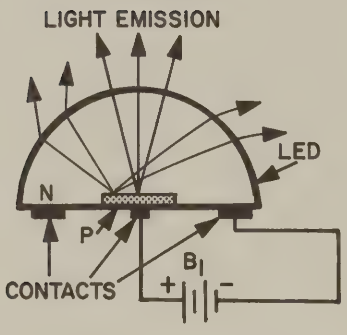


Figure 26

only a small percentage of the photons generated in a planar-type, gallium arsenide LED are released.

The light-emitting ability of an LED can be greatly increased by improving the basic planar construction. For example, an N-type gallium arsenide substrate can be formed into a hemisphere as shown in Figure 26, and a small P-type region can be diffused into the flat side or base. If the hemisphere has the proper diameter, nearly all of the photons generated at the PN junction will arrive at the surface at an angle that is less than the critical angle, and they will escape. This type of construction almost completely eliminates reflections and greatly improves the light-emitting efficiency of the LED.

Another means of improving the light-emitting efficiency of the basic LED shown in Figure 25 is to cover the flat structure with a dome (hemisphere) made of epoxy. The epoxy dome serves as a light-conducting medium which has the effect of increasing the critical angle of the basic planar structure. This technique is not as effective as the method just described; however, it will more than double the efficiency of a planar LED and provide sufficient light for many applications.

LED's which emit visible light are generally dome shaped. The dome effectively diffuses the light and improves its visibility. These LED's are rapidly replacing the small incandescent and neon lamps which have been used as indicators for many years. LED's are often used as blown fuse indicators, fault or warning indicators, circuit status indicators, and power-on indicators where they serve as simple on-off devices. However, they also find more complex applications in computers and other complex digital systems. In these complex digital systems, LED's are often grouped together to form displays which can produce various readout patterns such as numbers or letters. This same technique is also used to produce the numbers or digits that are displayed on devices such as pocket calculators and electronic wrist watches.

LED's that emit near-infrared (invisible) light may be dome shaped or they may be designed to emit light in a narrow beam. This is often accomplished by using reflectors or by altering the basic construction of the LED. Because infrared radiation is easily detected by silicon devices, the near-infrared light source is commonly used with photodiode and phototransistor detectors to perform a variety of functions. For example, near-infrared emitting LED's are now used in punched-card and paper tape readers. In this application, a number of LED's are arranged in an array so that the individual light beams produced by the LED's are projected through the holes in the card or paper tape. A similar array of photodiodes or phototransistors are used to detect the presence or absence of light beams and effectively determine the positions of the punched holes. Near-infrared emitting LED's are also used in intrusion detectors because the light beam produced is invisible and cannot be spotted by the intruder. These LED's also find applications in production line counters, industrial controls, optical communication systems and precision optical alignment systems.

When compared to a tungsten-filament (incandescent) lamp, the LED offers some surprising advantages. For example, the LED provides a relatively pure light which is restricted to a single color, while the tungsten lamp provides a white light which is spread over the visible and infrared portions of the light spectrum. The LED is a solid-state device and is therefore much more rugged then the tungsten lamp. The LED is smaller in size than a tungsten lamp and is more suitable for use in portable or miniaturized equipment. The light produced by the LED is easier to focus and control. The LED has an extremely long life and is much more reliable than the tungsten lamp. The LED also has a much faster response time. In other words, the light produced by the LED varies with drive current and very little delay is encountered. Tungsten lamps respond very slowly to changes in drive current. LED's also consume less power than tungsten lamps. Most LED's require several milliamperes to several hundred milliamperes of current, but practically all LED's require less than 2 volts of forward bias.

It would appear that LED's are superior to tungsten lamps in all ways. However, LED's have certain disadvantages which limit their use in some applications. For example, LED's produce less light than tungsten lamps and they cannot provide sufficient light for many applications. The LED requires dc power for operation, but the tungsten lamp can be used with either ac or dc power. The LED is also more expensive, but this disadvantage may be overcome as manufacturing techniques improve.

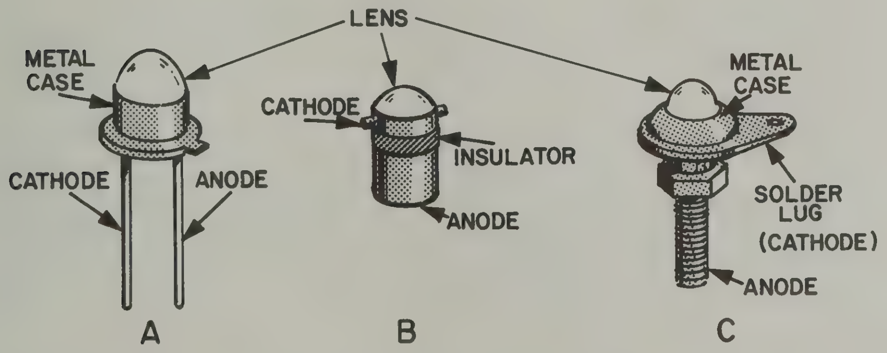


Figure 27

Figure 27 shows three commonly used types of LED's. The LED shown in Figure 27A emits visible light and is designed to be used as a visual indicator. A dome-shaped lens is used to increase the light output of the LED. The two leads provided at the base of the LED serve as anode and cathode connections. The LED shown in Figure 27B emits light in the near-infrared region. This LED is extermely small in size (approximately 0.1 inch in length) and is designed for use in high density applications where many LED's must be placed in a small area. It may be used in equipment such as punched-card readers and punched-tape readers. The LED is designed for easy insertion and removal. The LED shown in Figure 27C also emits light in the near-infrared region. However, this LED is designed to produce a substantially higher output light intensity. This LED is stud mounted to provide the maximum amount of heat sinking action. The LED is simply bolted to a metal plate or chassis (called a heat sink) which will absorb the heat generated by the LED. The stud serves as the anode, and the solder lug connects to the cathode as shown. This type of LED, when operated at currents of several hundred milliamperes, can produce a light intensity high enough to make it useful in industrial control applications and optical communications systems.

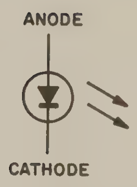


Figure 28

The symbol most commonly used to represent the LED is shown in Figure 28. This symbol closely resembles the symbol used for the photodiode previously discussed, except that the LED has arrowheads coming from, rather than going to, the symbol.

OPTICAL COUPLERS

The development of the LED has led to the development of another device which utilizes the principles of light emission as well as light detection. This relatively new device is basically a combination of two of the devices previously described. It consists of an LED, which operates in the near-infrared range, and a photodiode, phototransistor or photo SCR. This device is commonly referred to as an **OPTICAL COUPLER**, and it is used whenever complete electrical isolation is required between two circuits.

Optical couplers were available long before LED's were developed. However, these early devices used incandescent and neon lamps and were limited to certain low-frequency applications. We will therefore examine the modern optical coupler which utilizes the LED and which has become accepted as an industry standard.

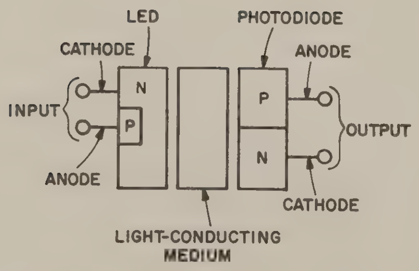


Figure 29

The basic construction of a modern optical coupler is shown in Figure 29. An LED and a photodiode are physically arranged so that the light produced by the LED is applied directly to the photodiode. The LED and photodiode are separated by either a thin layer, or sheet, or infrared light-transmitting glass or a gas-filled gap. To prevent unwanted light from entering the device, the components are usually encased in a plastic compound. The photons emitted by the LED are effectively piped, or transmitted, through the glass (or gas) to the photodiode which responds to the intensity of the light striking its surface. The glass sheet or gas-filled gap serves as a light-conducting medium to insure that the maximum amount of light is transferred from one device to the other. The two photo devices and the light-conducting medium are mounted in a single package with appropriate input and output leads attached to the LED and the photodiode.

The LED shown in Figure 29 must be forward biased to operate properly; however, the photodiode must be reverse biased. When the proper operating voltages are applied to the two photo devices, the circuit may be used to optically transfer a signal from input to output. In other words, when the current through the LED is made to increase, the light produced by the LED will also increase in intensity. This will, in turn, cause the photodiode to conduct more, which allows more current through the output terminals. However, when the current through the LED decreases, the LED produces less light. This causes the photodiode to conduct less and the output current to decrease. The current produced by the photodiode therefore varies in proportion to the current through the LED.

Optical couplers are used when electrical isolation is required between circuits. Because the signal is effectively transmitted over a light beam, there is no electrical coupling between the input and output leads. This means that the input and output circuits can operate at different potentials and do not have to use the same circuit ground. Optical couplers provide as much isolation as electromechanical relays and magnetically coupled transformers. In fact, they are often used as replacements for both of these devices in applications where high currents or voltages are not encountered.

The optical coupler shown in Figure 29 is capable of transferring either dc signals or ac signals (when properly biased) between its input and output leads. Because a photodiode is used to detect, or respond to, the light beam, the optical coupler has a very fast response time. This type of photocoupler is suitable for transferring signal frequencies as high as several megahertz. Unfortunately, the photodiode is capable of handling only small currents when it is reverse biased. Normally, the output current will be only a fraction of the applied input current. The current gain (ratio of output to input current) will therefore be quite low for optical couplers of this type.

When a greater current gain is required, a phototransistor is used instead of a photodiode. When a phototransistor is used, a current gain that is greater than one, or unity, can be obtained. However, the response time of the phototransistor is normally slower than the response time of a photodiode. Therefore, this type of optical coupler will not transfer very high frequencies like the photodiode type previously described.

When even greater gain is required, a photo Darlington amplifier can be used. In other words, two phototransistors can be connected in a photo Darlington configuration for detecting or responding to the light beam produced by the LED. Although this type of optical coupler will produce a current gain that is much greater than unity, it has a very slow response time and is suitable only for dc and relatively low-frequency ac signals.

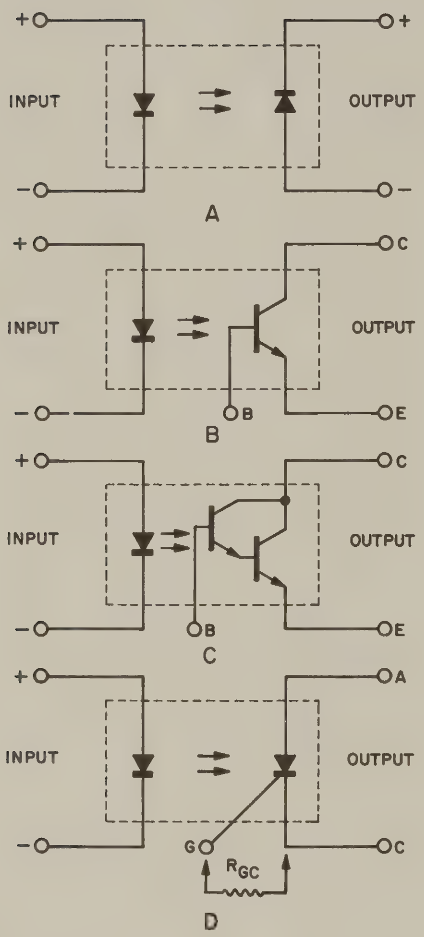


Figure 30

Photo SCR's may also be used in optical couplers to allow relatively large currents or voltages to be switched by an electrically isolated control signal. As with a conventional SCR, the control current is applied only for an instant to turn on the photo SCR. The photo SCR is then turned off by reducing the current through the photo SCR below its holding value. The gate, cathode and anode leads of the photo SCR are used so that it can be biased in the normal manner. A gate-to-cathode resistor is normally used to control the sensitivity of the photo SCR.

The symbols most commonly used to represent the optical couplers just described are shown in Figure 30. The symbol for the photodiode type of optical coupler is shown in Figure 30A. The plus and minus signs at the input and output terminals are included to show the proper polarity of the operating voltages. These signs will not necessarily appear with the symbol when it is used in a typical schematic diagram. Figure 30B shows the symbol of a phototransistor type of optical coupler. The emitter, base and collector leads of the output transistor are appropriately identified. Figure 30C shows the symbol of a photo Darlington type of optical coupler and Figure 30D shows the photo SCR type of optical coupler. Resistor R_{GC} represents the gate-to-cathode resistance which can be connected to the photo SCR to control the sensitivity of the optical coupler. This resistor is not an essential part of the optical coupler symbol.

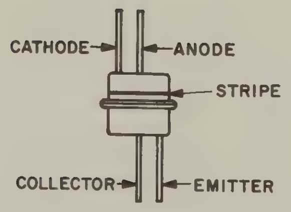


Figure 31

Optical couplers come in a variety of shapes and sizes. A typical optical coupler is shown in Figure 31; it utilizes an LED with a near-infrared light output and a phototransistor. Both of these devices are mounted in a single container as shown, using a gas-filled gap as the light-conducting medium. The container is a hermetically sealed metal can and the input and output leads are attached to each end of the can. Notice that only two leads (emitter and collector) are provided for the phototransistor and two leads (anode and cathode) are provided for the LED. The LED leads are identified by the stripe on the container as shown. The base lead is omitted on the phototransistor shown; however, other types of optical couplers are available with phototransistor base leads.

Near-infrared LED's and photosensitive silicon devices are used in most optical couplers. The silicon devices are highly sensitive to the near-infrared light, and near-infrared LED's are easily constructed from gallium arsenide.

APPLICATIONS OF PHOTOELECTRIC DEVICES

Now that you have examined the operation of some of the more important photoelectric devices, it is time to examine some basic applications of these devices. Because there are so many potential applications of photoelectric devices, it is impractical to describe them all. A few of the more basic applications are therefore presented.

Many of the photoelectric devices described in this lesson can be used to measure heat as well as light. However, the photoelectric device which is most often used for this purpose is the photovoltaic cell, because it requires no external battery and has a very long and stable life. A typical heat or temperature measuring instrument (often called a "pyrometer"), which uses a photovoltaic cell, is shown in Figure 32. The pyrometer utilizes a limiter resistor (R) (usually 50 to 300 ohms), a microammeter and a selenium photovoltaic cell. The selenium photovoltaic cell shown in Figure 32 is similar to the selenium photovoltaic cell shown in Figure 7. A layer of gold acts as a transparent electrode to the radiant energy, and the junction between the gold and selenium acts as a barrier layer. The radiant energy from the heated object passes through the glass faceplate and the water jacket to the photovoltaic cell. The cell develops an output voltage of the polarity shown. The output voltage is proportional to the frequency of the radiant energy, and the frequency is determined by the temperature of the radiating body. Therefore, the current indicated by the microammeter is a measurement of the temperature. The water jacket is used to prevent heat damage to the photovoltaic cell.

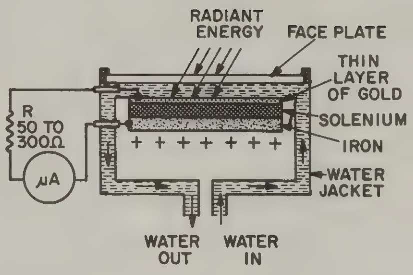


Figure 32

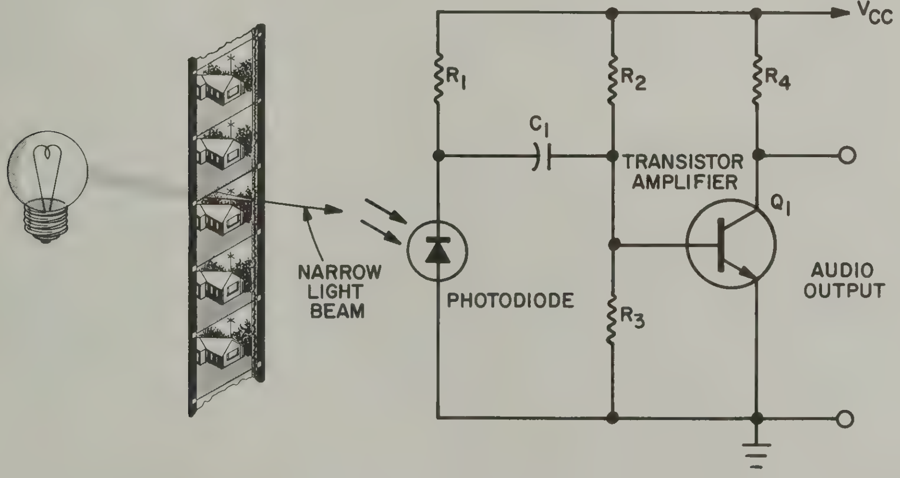


Figure 33

Figure 33 shows a typical application of a photodiode. Here, a silicon photodiode is used in a motion picture sound pickup system. Light from the "exciter" lamp is directed, by means of optical mirrors and lenses, to pass through the photographic image of sound recorded on one edge of the film. The beam of light is varied or modulated in accordance with the sound information on the film. The varying light beam, directed on the photodiode, causes the resistance of the photodiode to vary. Because the photodiode is in series with resistor R_1, the voltage across the photodiode will change. This changing voltage (audio) is coupled through C_1 to the base of the transistor amplifier, Q_1. An amplified audio voltage is obtained from the collector of the transistor. This output is applied to a power amplifier for the high power level reproduction required in theater auditoriums.

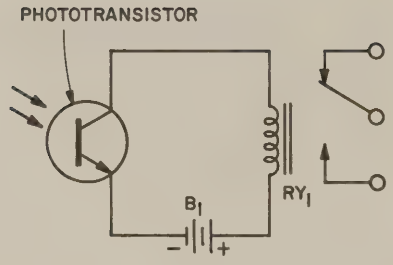


Figure 34

A typical application of a phototransistor is shown in Figure 34. This is a basic photoelectric relay circuit which uses a silicon phototransistor to control the operation of a sensitive electromechanical relay. When no light is applied to the phototransistor, the collector current is extremely low. This small current is not large enough to energize relay RY_1, and the contacts remain in the positions shown. However, when sufficient light is applied to the phototransistor, the collector current will increase and the relay will energize, thus causing the contacts to close. If the light is removed, the relay de-energizes and the contacts open. The phototransistor is therefore used to directly operate a relay which, in turn, may be used to control a substantial amount of current or voltage through its contacts. For example, a lamp or motor and its respective power source could be connected in series with the relay contacts for effective control by the applied light.

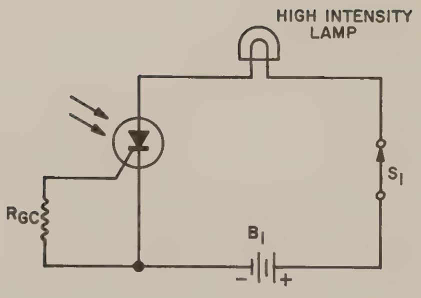


Figure 35

The circuit shown in Figure 35 performs the same basic function as the photoelectric relay circuit just described. However, the circuit shown in Figure 35 uses a photo SCR instead of a phototransistor and an electromechanical relay. In this circuit a photo SCR is used to control the power applied to a lamp. Switch S_1 is normally closed so that the photo SCR, the lamp and battery B_1 are all in series. When light is momentarily applied to the photo SCR, it triggers on and the lamp lights. To turn off the lamp, switch S_1 must be momentarily opened so that the current through the photo SCR is reduced below the required holding value. The photo SCR therefore functions as a light-controlled relay; however, this type of relay is often referred to as a dc latching relay. It can be used only with dc loads, and once it is activated, it remains activated (or latched) until switch S_1 is opened. The sensitivity of the photo SCR can be controlled by adjusting the value of resistor R_{GC}.

Figure 36 shows a typical application of an optical coupler. The optical coupler is used here to electrically isolate an amplifier circuit from the applied input signal. The phototransistor portion of the optical coupler, in conjunction with resistors R_1, R_2 and R_3, serves to bias transistor Q_1 at the proper operating point. Potentiometer R_4 permits adjusting the base current

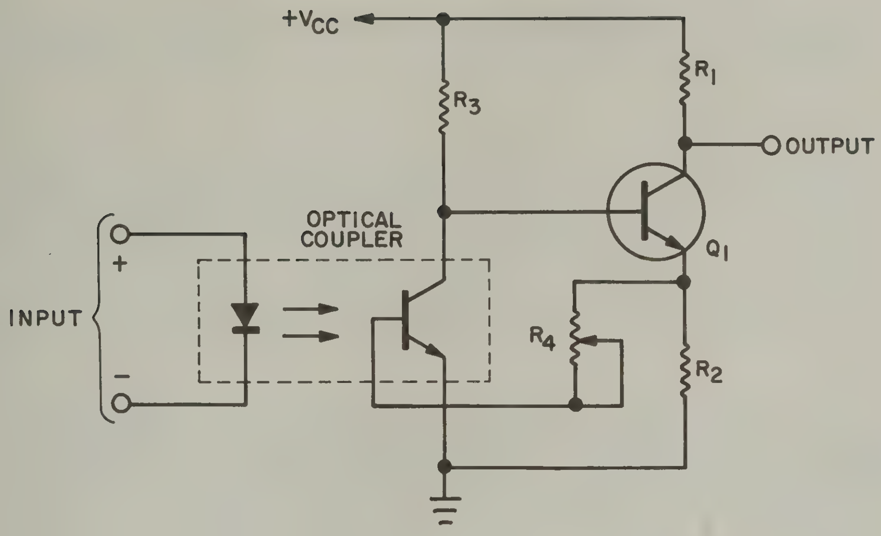


Figure 36

of the phototransistor which, in turn, controls the voltage at the base of Q_1. In other words, the potentiometer adjusts the operating point of the amplifier to an optimum point. The input signal applied to the LED portion of the optical coupler must be of the proper polarity, as shown. As the input signal varies in amplitude, the LED conducts accordingly, producing a light of varying intensity. AC signals can also be applied to the optical coupler when it is properly biased. In other words, the ac signal is used to control the dc forward bias applied to the LED. The phototransistor responds to the changes in light intensity and its resistance varies as it conducts more or less current. The voltage changes produced across the phototransistor are amplified by Q_1 and appear at the output of the amplifier.

SUMMARY

Light energy can be used in many applications in industry and in the home. In industry, light is often used to count, sort, measure levels, measure temperature and perform other services. In the home, light can be used in burglar alarms, automatic light switches to turn on the house lights when it gets dark and other useful applications.

The electronic instruments that perform these operations with light use special devices that either convert light energy directly into electrical energy or change their characteristics when illuminated. These devices operate on the photoelectric effect. The photoelectric effect refers to the action in certain materials which causes the atoms in the material to give up electrons when the material receives light energy.

One type of photoelectric device is the photoconductive cell. The internal resistance of a photoconductive cell depends upon the intensity of light falling on the cell. With no light on the cell, its internal resistance is high; however, when the cell is illuminated, the internal resistance decreases. The most common types of photoconductive cells are the lead sulphide, cadmium sulphide and cadmium selenide cells.

The photoelectric effect can also be used to form self-generating photovoltaic devices. A photovoltaic device develops an output voltage proportional to the intensity of light falling on it. The two common types of photovoltaic cells are the selenium cell and the silicon PN junction cell.

Light energy also affects the characteristics of a PN junction. If a PN junction is reverse biased, only a small electron flow occurs through the PN junction and the external circuit. Illuminating the PN junction, however, forms hole-electron pairs which cause an increase in reverse current. The reverse current through the PN junction, and thus the circuit current, can be controlled by varying the intensity of light falling on the junction. Devices of this type are called photodiodes.

A device that is light sensitive and provides amplification is the phototransistor. The phototransistor operates like a conventional transistor except that the emitter junction is forward biased by the light falling on the emitter junction. The phototransistor produces a greater output current than the photodiode and is more suitable in applications where sensitivity and gain are important.

When it is necessary to control or switch relatively large amounts of power, the photo SCR is often used. This device operates like a conventional SCR, but it is controlled by light instead of an input voltage.

Relatively new devices such as LED's and optical couplers are now being used in place of the earlier electromechanical devices. LED's are highly efficient sources of light energy that are replacing incandescent and neon lamps in many applications. Optical couplers utilize both LED's and photosensitive devices to achieve a high degree of electrical isolation between circuits. Optical couplers are effectively replacing transformers in many applications where low currents and voltages are encountered. They also function as relays in some circuits by providing a means of controlling relatively large currents and voltages with an electrically isolated control signal.

The following Practice Exercise questions cover the subjects which you have just studied. They are:

SOLID-STATE EMITTERS

OPTICAL COUPLERS

APPLICATIONS OF PHOTOELECTRIC DEVICES

25. Near-infrared LED's are usually made from (a) gallium phosphide, (b) gallium arsenide phosphide, (c) gallium arsenide.

26. LED's are capable of producing greater light intensities than conventional incandescent lamps. True or False?

27. An LED which uses a hemispherical or dome-shaped construction is more efficient than the planar type. True or False?

28. LED's are often designed to emit a white light which is spread over the visible and near-infrared portions of the light spectrum. True or False?

29. An LED will operate only when it is reverse biased. True or False?

30. Optical couplers are used in applications where (a) electrical isolation is required, (b) high gain is required.

31. What type of devices are used in the construction of an optical coupler?

32. All optical couplers have a current gain that is greater than unity. True or False?

33. Which optical coupler shown in Figure 30 would provide the greatest amplification of a low-level ac signal?

34. Which optical coupler shown in Figure 30 would be used to control or switch relatively large currents or voltages?

35. An optical coupler will always have two input and two output leads. True or False?

36. The basic pyrometer shown in Figure 32 utilizes a (a) photoconductive cell to measure temperature, (b) photovoltaic cell to measure temperature.

37. The gain of the circuit shown in Figure 33 would be greatly increased if the photodiode was replaced with a (a) photo SCR, (b) photoconductive cell, (c) phototransistor.

38. If a photodiode type of optical coupler were used in the circuit shown in Figure 36, the overall gain of the circuit would (a) decrease, (b) remain the same, (c) increase.

IMPORTANT DEFINITIONS

CADMIUM SELENIDE CELL—A photoconductive device that utilizes a sensitive layer of cadmium selenide on a glass or ceramic base.

CADMIUM SULPHIDE CELL—A photoconductive device that utilizes a sensitive layer of cadmium sulphide on a glass or ceramic base.

CANDLEPOWER—The unit of measure of light intensity. Under present standards, one candlepower is a certain fraction of the average light intensity of a set of 45 carbon-filament lamps at the National Bureau of Standards.

CRITICAL ANGLE—The angle at which photons are reflected and reabsorbed in a semiconductor material.

DARK CURRENT—The current passed by a photosensitive device when it is not illuminated.

DARK RESISTANCE—The internal resistance of a photosensitive device when it is not illuminated.

FOOT-CANDLE—The unit of measure of illumination. One foot-candle is equal to one lumen distributed over a surface of one square foot.

LEAD SULPHIDE CELL—A photoconductive device that utilizes a light-sensitive layer of lead sulphide on an iron or steel base.

LIGHT ACTIVATED SCR (LASCR)—See PHOTO SCR.

LIGHT CURRENT—The current passed by a photosensitive device when it is illuminated.

LIGHT-EMITTING DIODE (LED)—A device containing a semiconductor PN junction that emits light when forward biased.

LIGHT RESISTANCE—The internal resistance of a photosensitive device when it is illuminated.

LUMEN—The unit of measure of light flux. One lumen is the quantity of light falling on the inside area of a spherical shell equal to r^2; where r is the radius of the shell, from a one-candlepower source.

OPTICAL COUPLER—A device that uses an internally generated and controlled light beam to transfer a signal from input to output. The optical coupler usually employs an LED and a photosensitive device such as a photodiode, phototransistor or photo SCR.

PHOTOCELL—See PHOTOELECTRIC DEVICE.

IMPORTANT DEFINITIONS (Continued)

PHOTOCONDUCTIVE EFFECT—The action in certain materials that causes them to change their internal resistance when bombarded with light energy.

PHOTO DARLINGTON AMPLIFIER—A special type of phototransistor that utilizes two phototransistors connected in a Darlington arrangement to increase gain.

PHOTODIODE—A photovoltaic device that is used as a light-sensitive diode. The photodiode converts light energy into electrical energy.

PHOTOELECTRIC CELL—See PHOTOELECTRIC DEVICE.

PHOTOELECTRIC DEVICE—A device that converts light energy into electrical energy or which changes its electrical characteristics with changes in light.

PHOTOELECTRIC EFFECT—The action in certain materials that causes them to release electrons when they are bombarded with light energy.

PHOTOELECTRONS—The electrons emitted from a light-sensitive material when it is bombarded with light energy.

PHOTON—A little packet or bundle of light energy.

PHOTO SCR—A four-layer light-sensitive semiconductor device similar to a conventional SCR, but controlled by light instead of an input voltage.

PHOTOTRANSISTOR—A three-layer light-sensitive semiconductor device similar to a conventional transistor. The phototransistor responds to light applied to its basic region instead of an input base current.

PHOTOVOLTAIC DEVICE—A photoelectric device that develops a voltage when illuminated.

SELENIUM PHOTOVOLTAIC CELL—A photovoltaic device that utilizes a selenium layer and a barrier layer to produce an output voltage when illuminated.

SILICON PHOTOVOLTAIC CELL—A photovoltaic device that utilizes silicon material to form a PN junction that produces a voltage when illuminated.

SPECTRAL SENSITIVITY—The relative sensitivity of a photosensitive material to light. Generally, each type of material exhibits a maximum sensitivity to light waves of a specific wavelength or color.

THRESHOLD FREQUENCY—The frequency at which the photoelectric effect occurs.

PRACTICE EXERCISE SOLUTIONS

1. The lumen is a unit used to measure light flux. One lumen is the quantity of light from a one-candlepower source falling on a fraction of the inside surface of a sphere equal to r^2, where r is the radius of the sphere.
2. The foot-candle is the unit of illumination. One foot-candle is equal to one lumen distributed over a surface of one square foot.
3. Photoelectrons are those electrons which are emitted from a light-sensitive material which is subjected to light energy.
4. Photons are the little packets, or bundles, of light energy.
5. (b) spectral sensitivity.
6. red-infrared
7. threshold
8. decrease
9. True
10. dark
11. The term "light resistance" refers to the resistance of a photoelectric cell when it is illuminated.
12. (b) 750.
13. False—The interlocking contacts decrease the light resistance.
14. False—Photoelectrons are emitted by the light-sensitive selenium layer.
15. (a) an increase in the output voltage.
16. True
17. (b) an increase in reverse current.
18. (a) more current than a photodiode.
19. False—Some phototransistors are constructed with three leads.
20. (b) phototransistor.
21. False—The photo Darlington amplifier provides a very high gain, but it is one of the slowest of all junction photoelectric devices.

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7415A

EXAMINATION CHECK SHEET

1. B - A FOOT-CANDLE IS -- EQUAL TO 1 LUMEN DISTRIBUTED OVER A SURFACE OF 1 SQUARE FOOT.
The foot-candle is the basic unit of measure of illumination.

2. A - A CADMIUM SULPHIDE CELL IS A TYPE OF -- PHOTOCONDUCTIVE CELL.
The cadmium sulphide cell is essentially a resistor that changes value when illuminated. The resistance of the device decreases as light intensity increases.

3. C - IN THE PHOTODIODE CIRCUIT OF FIGURE 13, AN INCREASE IN LIGHT INTENSITY CAUSES -- AN INCREASE IN REVERSE CURRENT.
The photodiode must be reverse biased to operate properly. The reverse current through the photodiode varies in direct proportion to the applied light.

4. A - WHEN COMPARED WITH THE PHOTODIODE, THE PHOTOTRANSISTOR OFFERS -- A HIGHER OUTPUT CURRENT FOR A GIVEN LIGHT INTENSITY.
The phototransistor acts like a photodiode and transistor amplifier all in one unit and therefore it passes a much higher current.

5. D - THE CURRENT GAIN OF THE PHOTO DARLINGTON AMPLIFIER IN FIGURE 19 IS EQUAL TO -- THE CURRENT GAIN OF THE FIRST TRANSISTOR MULTIPLIED BY THE CURRENT GAIN OF THE SECOND TRANSISTOR.
As with a conventional Darlington amplifier circuit, the overall current gain must equal the beta of the first transistor times the beta of the second transistor.

6. A - A PHOTO SCR IS OFTEN USED IN APPLICATIONS WHERE -- RELATIVELY HIGH CURRENTS MUST BE CONTROLLED BY LIGHT.
The photo SCR is essentially a light-controlled switch, except that light is used to turn on the photo SCR instead of a voltage.

7. A - THE LED IS ESSENTIALLY A PN JUNCTION DIODE WHICH -- EMITS LIGHT WHEN FORWARD BIASED.
The intensity of light is determined by the amount of forward current through the LED.

8. B - THE LIGHT PRODUCED BY AN LED IS -- RELATIVELY PURE AND RESTRICTED TO A SINGLE COLOR.
The color of the light produced by an LED is determined by the type of semiconductor material used in its construction.

9. B - A MODERN OPTICAL COUPLER WILL OFTEN CONTAIN -- AN LED AND A PHOTOTRANSISTOR.
An LED is also commonly used in conjunction with other devices such as a photodiode, a photo Darlington amplifier or a photo SCR.

10. A - THE MATERIAL MOST COMMONLY USED IN THE CONSTRUCTION OF PHOTODIODES, PHOTOTRANSISTORS AND OTHER PHOTOSENSITIVE DEVICES WHICH UTILIZE PN JUNCTIONS IS -- SILICON.
Silicon photosensitive devices respond well to the light produced by standard incandescent lamps and LED's, and may therefore be used in many applications.

QUESTIONS

IMPORTANT—These instructions **MUST** be accurately followed to avoid loss, or errors in grading.

Indicate your answer on this sheet by filling in the box for the most correct answer to each question, as illustrated in the example below.

When all questions have been answered, place the answer card in the proper position to line up the boxes on the card with the boxes on the sheet.

Next, copy the complete lesson code into the space provided on the card, and fill in the answer boxes to correspond with those previously filled in on this sheet.

Before mailing, be certain your correct student number, name and address appear on the card.

LESSON CODE
7415A

Example: A cube has

A ☐ B ☐ C ■ D ☐

(A) two sides. (B) four sides.
(C) six sides. (D) eight sides.

1. A ☐ B ☒ C ☐ D ☐

A foot-candle is
(A) the amount of light developed by a 1-candlepower source. (B) equal to 1 lumen distributed over a surface of 1 square foot. (C) the light falling on a surface area of r^2, where r is the radius of a sperical shell. (D) a measure of light flux.

2. A ☒ B ☐ C ☐ D ☐

A cadmium sulphide cell is a type of
(A) photoconductive cell. (B) photovoltaic cell. (C) phototransistor. (D) photodiode.

3. A ☐ B ☐ C ☒ D ☐

In the photodiode circuit of Figure 13, an increase in light intensity causes
(A) a decrease in forward current. (B) a decrease in reverse current. (C) an increase in reverse current. (D) an increase in forward current.

4. A ☒ B ☐ C ☐ D ☐

When compared with the photodiode, the phototransistor offers
(A) a higher output current for a given light intensity. (B) a much lower dark current. (C) a much faster response. (D) a lower output current for a given light intensity.

5. A ☐ B ☐ C ☐ D ☒

The current gain of the photo Darlington amplifier shown in Figure 19 is equal to
(A) the current gain of the output transistor. (B) the current gain of the first transistor plus the current gain of the second transistor. (C) the current gain of the first transistor. (D) the current gain of the first transistor multiplied by the current gain of the second transistor.

6. A ☒ B ☐ C ☐ D ☐

A photo SCR is often used in applications where
(A) relatively high currents must be controlled by light. (B) low-level ac signals must be amplified. (C) extremely low currents must be controlled by light. (D) high-level alternating currents must be amplified.

7. A ☒ B ☐ C ☐ D ☐

The LED is essentially a PN junction diode which
(A) emits light when forward biased. (B) emits light when reverse biased. (C) responds to light when reverse biased. (D) responds to light when forward biased.

8. A ☐ B ☒ C ☐ D ☐

The light produced by an LED is
(A) spread over the visible and near-infrared light spectrum. (B) relatively pure and restricted to a single color. (C) always in the near-infrared range. (D) always in the visible range.

9. A ☐ B ☒ C ☐ D ☐

A modern optical coupler will often contain
(A) an LED and a photoconductive cell. (B) an LED and a phototransistor. (C) a photovoltaic cell and a phototransistor. (D) a photodiode and a phototransistor.

10. A ☒ B ☐ C ☐ D ☐

The material most commonly used in the construction of photodiodes, phototransistors and other photosensitive devices which utilize PN junctions is
(A) silicon. (B) gallium arsenide. (C) gallium phosphide. (D) germanium.

PRACTICE EXERCISE SOLUTIONS (Continued)

22. True

23. (b) gate-to-cathode resistance.

24. False—The photo SCR turns on when light is applied but it can only be turned off by reducing its anode current below its particular holding value.

25. (c) gallium arsenide.

26. False—LED's produce much lower light intensities than incandescent lamps.

27. True

28. False—The LED provides a relatively pure light if a single color.

29. False—The LED must be forward biased to emit light.

30. (a) electrical isolation is required.

31. An optical coupler usually contains a near-infrared LED and a photosensitive device such as a photodiode, phototransistor or photo SCR. The two devices are separated by a light-conducting medium, which is usually a special type of infrared light-transmitting glass or a gas-filled cavity.

32. False—Optical couplers which utilize photodiodes have a current gain that is less than unity.

33. The photo Darlington optical coupler shown in Figure 30C would provide the greatest amplification of either a dc or an ac signal.

34. The photo SCR type of optical coupler shown in Figure 30D would be used to switch relatively large currents or voltages.

35. False—The photo SCR type of optical coupler requires two input leads and three output leads. The same is also true for some phototransistor types.

36. (b) photovoltaic cell to measure temperature.

37. (c) phototransistor.

38. (a) decrease.

QUESTIONS

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LESSON CODE
7415A

Example: A cube has
A ☐ B ☐ C ■ D ☐
(A) two sides. (B) four sides.
(C) six sides. (D) eight sides.

1. A ☐ B ☒ C ☐ D ☐
A foot-candle is
(A) the amount of light developed by a 1-candlepower source. (B) equal to 1 lumen distributed over a surface of 1 square foot. (C) the light falling on a surface area of r^2, where r is the radius of a sperical shell. (D) a measure of light flux.

2. A ☒ B ☐ C ☐ D ☐
A cadmium sulphide cell is a type of
(A) photoconductive cell. (B) photovoltaic cell. (C) phototransistor. (D) photodiode.

3. A ☐ B ☐ C ☒ D ☐
In the photodiode circuit of Figure 13, an increase in light intensity causes
(A) a decrease in forward current. (B) a decrease in reverse current. (C) an increase in reverse current. (D) an increase in forward current.

4. A ☒ B ☐ C ☐ D ☐
When compared with the photodiode, the phototransistor offers
(A) a higher output current for a given light intensity. (B) a much lower dark current. (C) a much faster response. (D) a lower output current for a given light intensity.

5. A ☐ B ☐ C ☐ D ☒
The current gain of the photo Darlington amplifier shown in Figure 19 is equal to
(A) the current gain of the output transistor. (B) the current gain of the first transistor plus the current gain of the second transistor. (C) the current gain of the first transistor. (D) the current gain of the first transistor multiplied by the current gain of the second transistor.

6. A ☒ B ☐ C ☐ D ☐
A photo SCR is often used in applications where
(A) relatively high currents must be controlled by light. (B) low-level ac signals must be amplified. (C) extremely low currents must be controlled by light. (D) high-level alternating currents must be amplified.

7. A ☒ B ☐ C ☐ D ☐
The LED is essentially a PN junction diode which
(A) emits light when forward biased. (B) emits light when reverse biased. (C) responds to light when reverse biased. (D) responds to light when forward biased.

8. A ☐ B ☒ C ☐ D ☐
The light produced by an LED is
(A) spread over the visible and near-infrared light spectrum. (B) relatively pure and restricted to a single color. (C) always in the near-infrared range. (D) always in the visible range.

9. A ☐ B ☒ C ☐ D ☐
A modern optical coupler will often contain
(A) an LED and a photoconductive cell. (B) an LED and a phototransistor. (C) a photovoltaic cell and a phototransistor. (D) a photodiode and a phototransistor.

10. A ☒ B ☐ C ☐ D ☐
The material most commonly used in the construction of photodiodes, phototransistors and other photosensitive devices which utilize PN junctions is
(A) silicon. (B) gallium arsenide. (C) gallium phosphide. (D) germanium.

ELECTRONIC METERS

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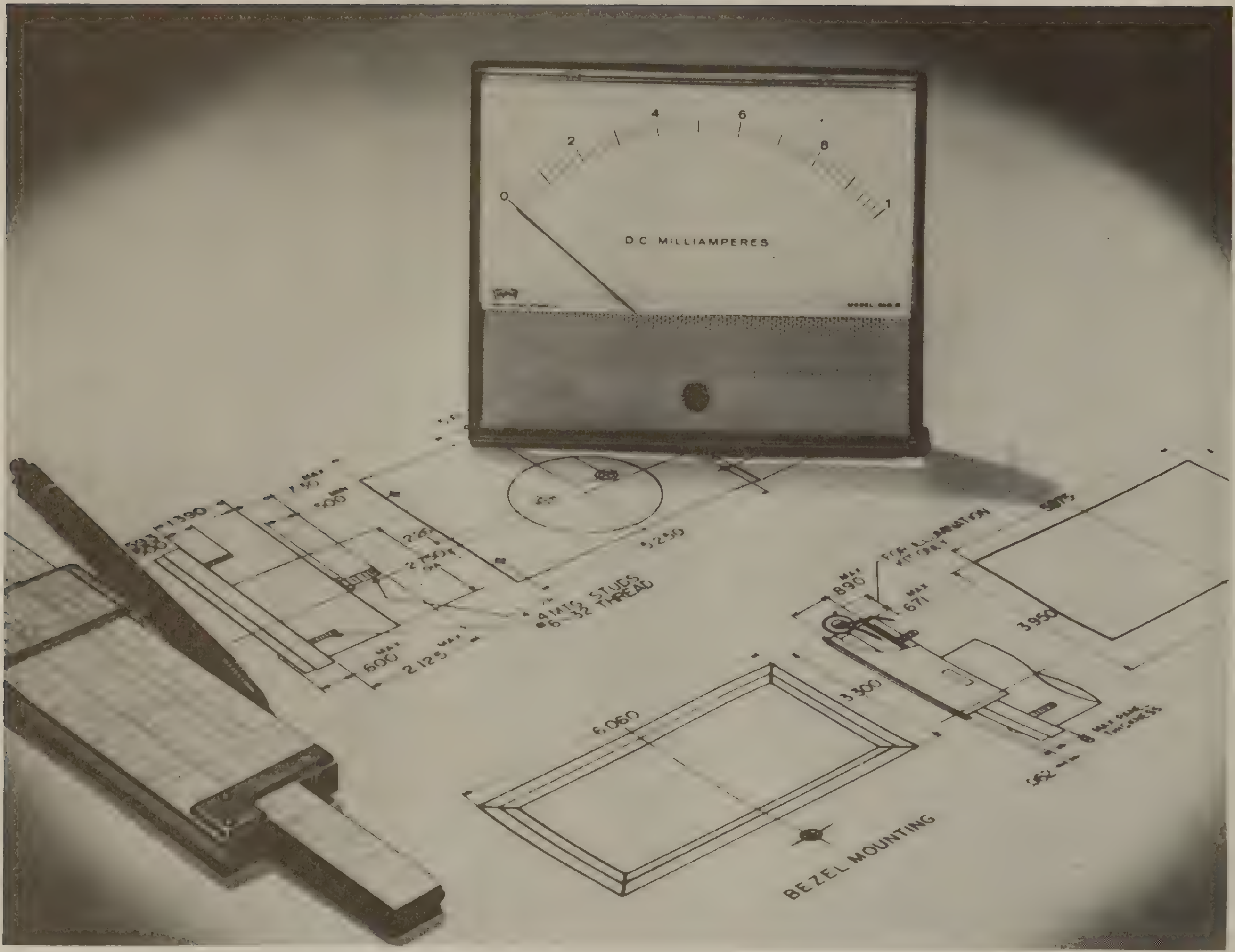

The D'Arsonval meter movement is the heart of most electronic meters. By employing an electronic amplifier ahead of the meter movement, any desired sensitivity or selectivity can be obtained.

Courtesy The Triplett Electrical Instrument Co.

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The reward of one duty is
the power to fulfill another.
—Thomas Carlyle

ELECTRONIC METERS

Meters are instruments that measure the effects of electricity. Depending on its circuit arrangement, a meter may measure voltage, current or resistance. There are many types of meters available. Some use transistors or vacuum tubes to increase the meter's sensitivity or extend its limits of operation. We will use the term **ELECTRONIC METER** to describe a direct reading meter that uses transistors or vacuum tubes. A meter which is only an electromechanical device will be called an **ELECTRIC METER.**

Our discussion will center on those meters which utilize electromechanical meter movements since they are by far the most widely used types at this time. However, we will conclude by briefly examining a special type of meter which does not use any electromechanical device and which provides extremely accurate measurements.

METERS AND METER CHARACTERISTICS

Most electric and electronic meters are similar in two respects. One similarity is that the two meters generally use some type of meter movement such as a **D'ARSONVAL METER MOVEMENT** or **TAUT-BAND METER MOVEMENT.** The pointer deflection depends on the amount of current through the meter movement.

The other similarity is that both types of meters use some type of input circuit. Meter input circuits are basically groups of resistors placed in series or parallel with the meter movement in an electric meter, or at the input to a meter amplifier in an electronic meter. These resistors are usually referred to as **SHUNTS** when used in ammeters, **MULTIPLIERS** in voltmeters, or simply, **RANGE RESISTORS,** in other instruments. They are used to increase the range of measurements that can be made with the meter.

A switch that selects the resistor or combination of resistors to give the desired range of readings is called a **RANGE SWITCH.** If the meter is a multiple function unit, such as a combination of ammeter, voltmeter and ohmmeter, it may also include a **FUNCTION SWITCH** to select the proper circuitry for the type of measurement desired.

Figure 1A shows the electric meter in block diagram form. This meter is divided into two blocks: the input circuits and the meter movement. Figure 1B shows the block diagram of an electronic meter. This meter is divided into four blocks: the input circuits, a transistor or vacuum tube amplifier, a power supply and a meter movement. The distinguishing feature of an

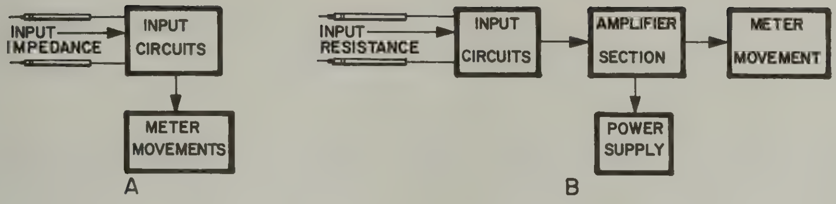


Figure 1

electronic meter, when compared to an electric meter, is the electronic amplifier and its power supply.

LOADING AND IMPEDANCE

Although electric and electronic meters both use current from the circuit being tested, there often is a considerable difference in the amounts of current required. The electric meter uses some of the test circuit current to operate the meter movement directly. The electronic meter uses smaller amounts of test circuit current to develop a signal for the meter amplifier. The operating current for the meter movement of the electronic meter is supplied by the power supply and amplifier.

The action of a meter using current from a test circuit is called **LOADING.** Loading can cause an incorrect meter reading because it disturbs the voltages or currents normally present in the circuit being tested.

When a meter is connected into a test circuit, a new circuit is formed that consists of the internal resistance of the meter in parallel or in series with part of the test circuit. This can change the operating conditions of the test circuit enough to make the measurements incorrect. The amount of test circuit loading depends on the internal resistance of the meter being used. Therefore, different meters may have different loading effects. The internal meter resistance, often referred to as the meter **INPUT RESISTANCE,** is the total resistance that a meter offers to test circuit current.

The internal resistance of the electric meter of Figure 1A depends on the combined resistance of the input circuits and the meter movement. In an electric voltmeter, each change of the range switch setting connects different multiplier resistors in series with the meter movement, changing the input resistance of the meter. The electronic meter shown in Figure 1B also has a set of voltage divider resistors between the input jacks. However, these resistors have much higher resistance values than do the multiplier resistors used in an electric meter. This is because only a small sample current or voltage is needed for the amplifier of the electronic meter. The meter movement is part of the amplifier. Because of this circuit arrangement, the input resistance of the electronic meter remains high, and almost constant, as the setting of the range switch is changed.

The high **INPUT IMPEDANCE** of an electronic meter is supplied by its amplifier input sections. The term "impedance" is used because it refers to the ~~total opposition a~~ circuit offers to current. Impedance is a combination of resistance and reactance. This reactance includes the capacitive effect of the wiring in the input circuits and the input capacitance of the vacuum tube or transistor.

Figure 2 shows the effects of input impedance on the loading of test circuits. The test circuit has a total series resistance of 40,000 ohms (R_1 = 20,000 ohms and R_2 = 20,000 ohms) connected across a 100-volt battery. Neglecting the meter circuit for a moment, the current through the 40,000-ohm circuit resistance with 100 volts applied is $^{100}/_{40,000}$, or .0025 ampere. With two equal value resistors across the 100-volt source, the voltage across each resistor is half the source voltage, or 50 volts.

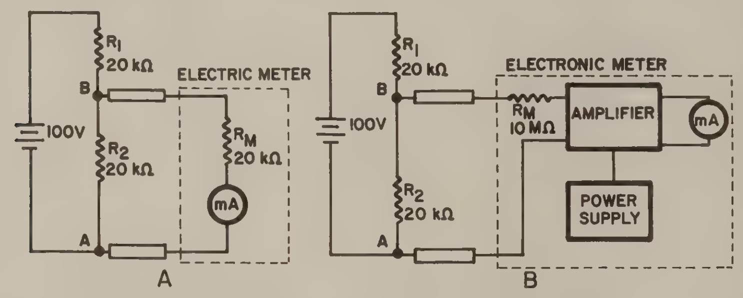


Figure 2

Now, suppose that you connect an electric meter with an internal resistance, R_M, of 20,000 ohms across resistor R_2, as shown in Figure 2A. With the meter circuit and R_2 in parallel, the effective resistance from point A to point B is 10,000 ohms. The total circuit resistance is now only 30,000 ohms instead of the original 40,000 ohms. Therefore, the total circuit current increases from .0025 amp to .0033 amp. Since the value of R_2 has been effectively changed by R_M, the voltage measured across R_2 will not be the TRUE VALUE. In this instance, the measured voltage across R_2 will be .0033 amp × 10,000 ohms, or 33.3 volts.

The same test circuit is used in Figure 2B, but an electronic meter with a 10-megohm input impedance is connected across R_2. The effective resistance of the parallel combination of R_2 and the electronic meter is about 19,960 ohms. The total circuit resistance is now about 39,960 ohms, and Ohm's Law shows that the current is approximately .002503 ampere. Now, the measured voltage across R_2 will be .002503 ampere × 19,960 ohms, or 49.96 volts.

Let's compare the effects of the two meter circuits in Figure 2. With the electric meter the measured voltage was 33.3 volts, and with the electronic meter the measured voltage was 49.96 volts. In this circuit, the electric meter causes an error of well over 30%, which cannot be tolerated in most situations. However, the electronic meter causes an error of less than 1% in this circuit, which can be disregarded in most situations.

In summary, we can say that the electronic meter reduces the loading effect caused by a meter being connected to a circuit because it leaves the circuit operating conditions almost unchanged. This is an advantage, particularly in low-power, high-impedance circuits where electric meters can cause considerable disturbance and error.

BALANCED BRIDGE

The use of an amplifier in a meter provides a high input impedance which results in very little loading of the circuit under test. Another advantage is that the amplifier increases the effective sensitivity of the meter movement while isolating the meter movement from the test circuit. The sensitivity of the meter movement is increased because a very small test signal is amplified to cause greater deflection of the meter pointer. This permits the measurement of voltages that are too small to produce deflection of the average electric meter.

In addition to amplification and high input impedances, the amplifier offers protection for the meter movement by isolating it from the test circuit. The internal characteristics of the amplifier limit the amount of plate or collector current which operates the meter movement. This eliminates the chance of damaging the meter movement because of large currents or voltages in the test circuit.

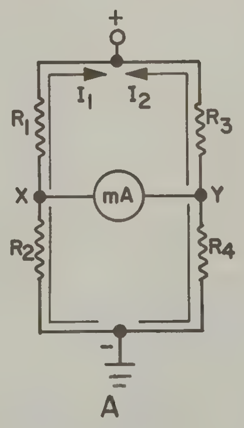


Figure 3

A common circuit used in electronic meter amplifiers is the **BRIDGE CIRCUIT.** Figure 3A shows a simple bridge arrangement that has two circuit branches, $R_1 + R_2$ and $R_3 + R_4$. The voltage applied to each branch, between ground and the positive terminal (+), causes current I_1 in one branch, and current I_2 in the other. A meter movement is connected between the top ends of R_2 and R_4, at the points labeled X and Y. This divides the bridge circuit into four arms, R_1, R_2, R_3 and R_4.

The potential at X is due to current I_1 in the R_1R_2 branch, and the potential at Y is due to current I_2 in the R_3R_4 branch. Any change of resistance in either branch will change the current in that branch and thereby change the potential at point X or Y. If $R_1 = R_3$ and $R_2 = R_4$, the potential at point X equals that at point Y, there is no current through the meter, and the bridge is said to be BALANCED. The meter pointer will not deflect.

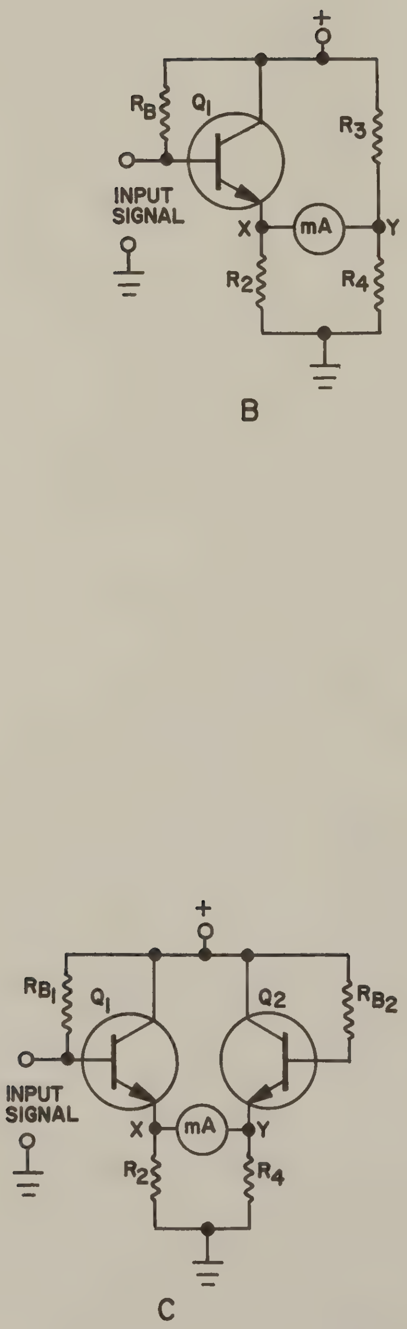


Figure 3

If we replace R_1 with a smaller value or resistance, the total resistance of the left branch decreases and current I_1 increases. More voltage appears across R_2 and less across R_1, making point X more positive than point Y. Current through the meter movement from point Y to point X causes the meter pointer to deflect. The meter pointer will deflect an amount proportional to the current in the meter movements. The current depends upon the difference of potential between points X and Y. Now, the bridge circuit is said to be UNBALANCED.

In an electronic amplifier bridge, one or more of the resistors may be replaced with active devices such as vacuum tubes or transistors. In earlier test instruments, vacuum tubes were used extensively, but today, transistors are commonly used in bridge circuits since they are more reliable and also more efficient. A typical transistorized bridge circuit is shown in Figure 3B. Notice that transistor Q_1 is being used instead of resistor R_1. Base resistor R_B is also added so that transistor Q_1 can be properly biased. By adjusting the value of resistor R_B, it is possible to control the conduction of Q_1, and therefore vary the resistance of that branch of the bridge circuit. Normally, the transistor is biased so that its collector-to-emitter voltage drop is equal to the voltage drop across R_3. Since resistors R_2 and R_4 are equal in value, the bridge circuit will be effectively balanced. If the meter movement is again placed between the two branches at points X and Y, the meter pointer will rest at its zero point because the bridge is balanced at this time.

The bridge circuit of Figure 3B responds to voltage changes at the base of transistor Q_1. If the Q_1 base voltage is sufficiently positive, the transistor's base current will increase, and Q_1 will conduct more, resulting in more current through the branch containing Q_1. The increased branch current causes a larger voltage drop across R_2, which results in less voltage across Q_1.

The voltage at point Y remains constant because the values of R_3 and R_4 are fixed. However, the voltage at point X is now positive with respect to point Y because of the larger voltage drop across R_2. This difference of potential across the meter movement causes current through the meter from point Y to point X, deflecting the meter pointer.

If the positive Q_1 base voltage is increased further, the transistor will conduct even more. The voltage across R_2 will increase, and a greater difference of potential will exist between points X and Y. The current through the meter will therefore increase and the meter pointer will deflect even further. This means that the meter provides an indication that is proportional to the voltage applied to the base of Q_1.

Although the single transistor bridge circuit just described can be used in actual meter circuits, it is common practice to use two transistors. A bridge circuit which employs two transistors is shown in Figure 3C. Transistor Q_2

replaces resistor R_3, just as transistor Q_1 replaced resistor R_1 in the original bridge circuit.

If the two base resistors (R_{B_1} and R_{B_2}) are adjusted so that the two transistors conduct equally, the voltage across R_2 and the voltage across R_4 will be equal. The difference of potential between points X and Y will be zero and there will be no current through the meter. This indicates that the bridge circuit is balanced.

Transistor Q_2 does not receive an input signal, but, instead serves as a reference voltage source and performs the same basic function as does resistor R_3 in Figure 3B. The bridge circuit conditions are changed only by variations in the Q_1 base voltage, and therefore the circuit operates in the same basic manner as the one-transistor circuit of Figure 3B. However, a definite advantage of the two-transistor circuit is that both sides of the circuit have nearly identical temperature characteristics. The two-transistor circuit is therefore more stable over long periods of time and it requires fewer adjustments.

The two-transistor bridge circuit is commonly used in electronic meters. Additional components are also required for balancing and controlling the voltages applied to the circuit. A variable resistor is often connected to one or more arms of the bridge circuit so that the circuit can be easily balanced before measurements are made. The variable resistor is adjusted for a zero meter reading, and is generally referred to as the ZERO ADJUST control. An input attenuator (made up of resistors) is used to reduce the test voltages applied to the bridge circuit, and switches are used to control the range of voltages which are applied to the circuit.

Because an electronic meter usually has an extremely high input impedance (to prevent loading), additional circuitry is required to compensate for the relatively low input impedance of the transistors. This is generally accomplished by adding an additional amplifier stage (usually one or more transistors) with a negative feedback arrangement to increase the transistor circuit input impedance.

Another commonly used bridge circuit is shown in Figure 4. This circuit employs two field-effect transistors (FET's) instead of two junction transistors, as did the circuit of Figure 3C. This circuit is essentially a solid-state version of the vacuum tube circuit that was used in vacuum tube voltmeters (VTVM's). The FET's shown here are N-channel types, and are biased in the same manner as vacuum tubes. Resistors R_2 and R_4 provide the necessary bias voltages for Q_1 and Q_2, respectively. The Q_1 gate (G) is connected to ground through base resistor R_g, and the Q_1 source (S) is connected to the positive side of resistor R_2. The Q_2 gate is connected directly to ground, and the Q_2 source is connected to the positive side of resistor R_4.

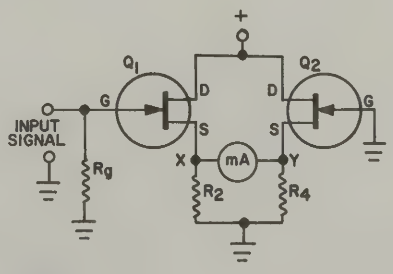


Figure 4

With equal bias voltages and identical characteristics, the FET's will conduct equal amounts of current, and the voltages across R_2 and R_4 will be equal. The difference of potential between points X and Y will be zero and there will be no current through the meter, indicating that the bridge circuit is balanced.

Input signals, developed across R_g, are applied to the Q_1 gate, and Q_2 serves as a reference FET because its bias voltage is held constant. When a positive voltage is applied to the Q_1 gate, Q_1 conduction increases, which increases the voltage across R_2. Therefore, the voltage at point X becomes positive with respect to point Y, and there is current through the meter from point Y to point X. If the input voltage increases further, the meter pointer will deflect further by an amount proportional to the change in input voltage.

The FET bridge circuit therefore performs the same basic function as the transistorized bridge circuit. However, the FET circuit has a distinct advantage. Because an FET has an inherently high input impedance, additional circuitry is not required solely for the purpose of maintaining a high impedance at the input of the meter circuit. Only an additional input attenuator and the usual range and zero adjust controls are required to complete the FET electronic meter circuit.

Transistors and FET's are widely used in electronic amplifier bridge circuits because they are compact and highly efficient. The low operating voltages required for these devices make them ideally suited for use in portable, battery-operated electronic meters.

GENERAL PURPOSE TRANSISTORIZED VOLTMETER

The most modern general purpose electronic meter available today is the **TRANSISTORIZED VOLTMETER,** abbreviated **TRVM.** The TRVM uses transistors rather than vacuum tubes in its amplifier section, and effectively replaces the older **VACUUM TUBE VOLTMETER (VTVM)** that was once widely used. There are several advantages in using transistors instead of vacuum tubes. For example, the TRVM requires lower operating voltages for the meter amplifier. Also, no heater supply is necessary. Because of these reduced power requirements, it is more practical to operate a transistorized meter from self-contained batteries. This makes it more portable and adaptable to field work than most general purpose VTVM's.

Figure 5 shows the TRVM designed by DeVry Institute of Technology. It can be used to measure ac or dc voltages and resistance, and it can also be used to measure a wide range of direct current. This is an advantage, particularly when working on transistor circuits.

The following Practice Exercise questions cover the subjects which you have just studied. They are:

METERS AND METER CHARACTERISTICS

LOADING AND IMPEDANCE

BALANCED BRIDGE

1. Into what two general groups are meters divided?

2. What sections do both meter types usually have in common?

3. Compared to the electric meter, the electronic meter requires (a) more current from the test circuit, (b) less current from the test circuit.

4. When the electronic meter is used to measure the voltage drop across a resistor, the current for the meter movement is supplied by (a) the test circuit, (b) the power supply and amplifier section.

5. A meter loads a test circuit when the meter uses current from the test circuit. True or False?

6. The amount of loading of a test circuit by a meter is determined by the (a) internal meter resistance, (b) ability of the meter to measure resistance.

7. The input impedance of an electronic meter is the total opposition the meter offers to test circuit current. True or False?

8. Explain what is meant by balance in a bridge circuit.

9. In Figure 3B, Q_1 acts as a variable (a) capacitor, (b) inductor, (c) resistor.

10. What are the reasons for using reference transistor Q_2 in the circuit of Figure 3C?

11. **What is the purpose of a ZERO ADJUST control in most electronic meters?**

12. **If there is no voltage present in the bridge section of an electronic meter, what portion of the unit might be the source of the trouble?**

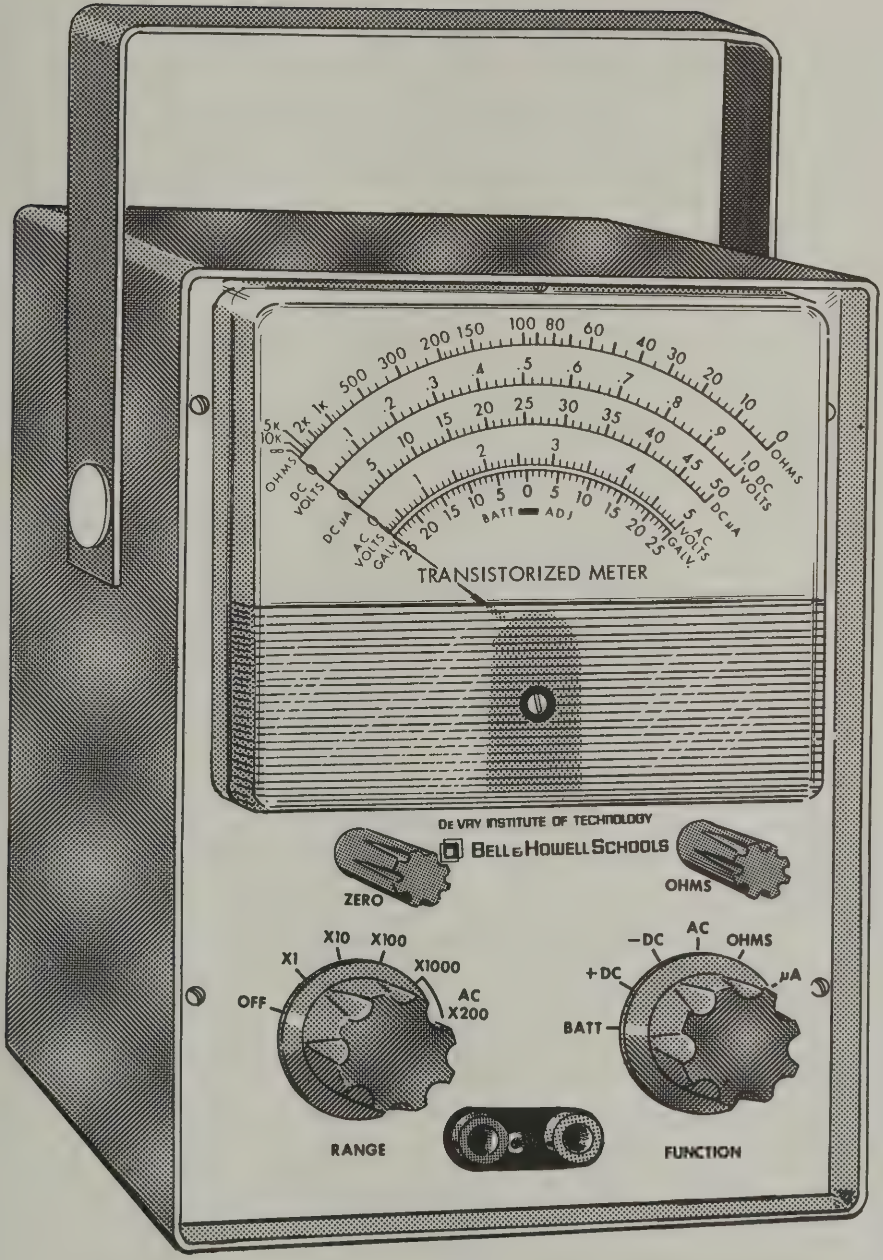


Figure 5

Meter Amplifier and Meter Movement

Figure 6 shows the schematic of the TRVM developed by DeVry Institute of Technology. The amplifier section of the TRVM contains four transistors. This particular amplifier arrangement is referred to as a **DIFFERENTIAL AMPLIFIER.**

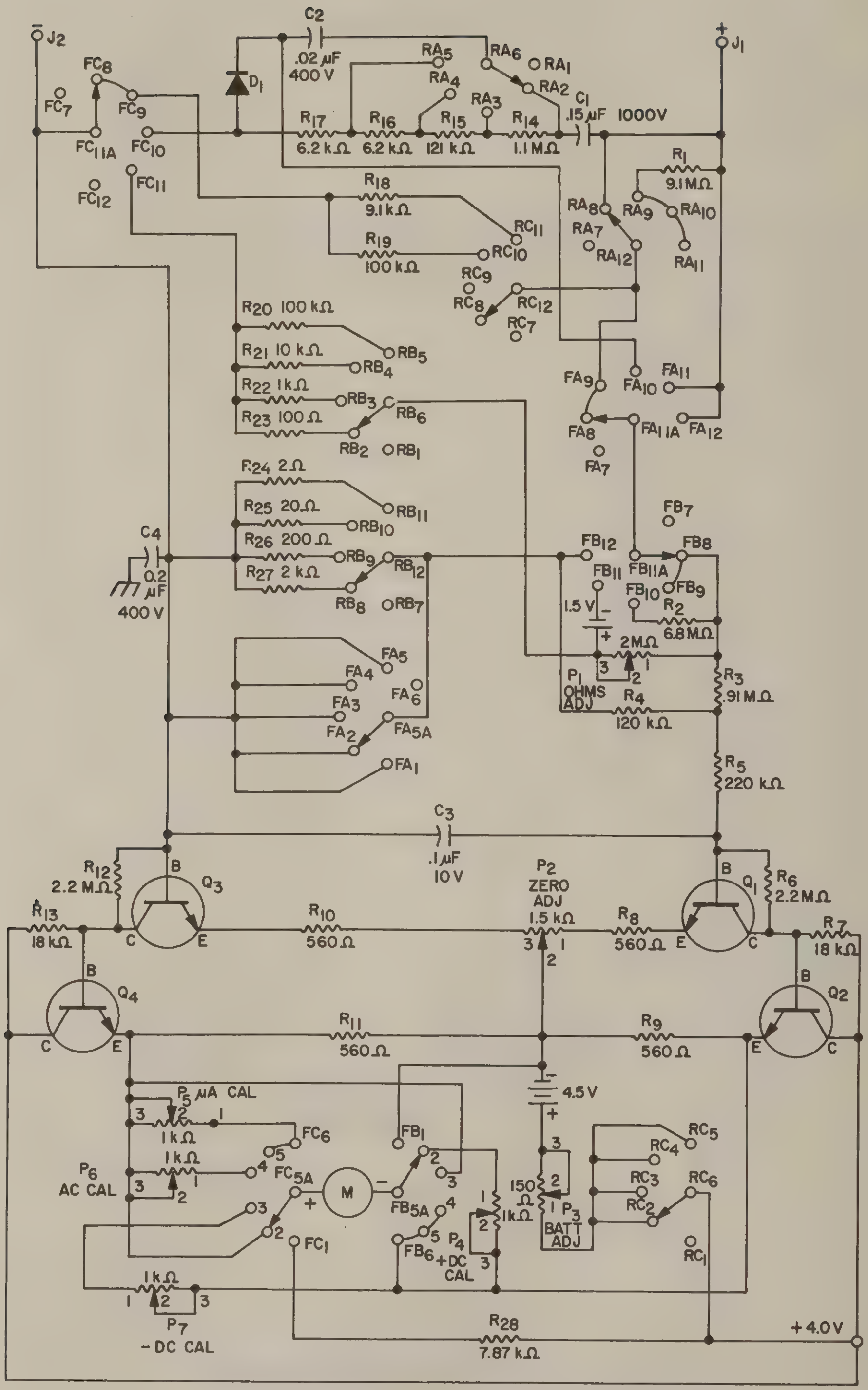


Figure 6

Figure 7A is a partial schematic of the TRVM that shows the differential amplifier. In this circuit, resistors R_3 and R_4 are part of a voltage divider between the input circuits and the transistors. Capacitor C_4 offers a low impedance path between one of the input jacks and the metal case when the

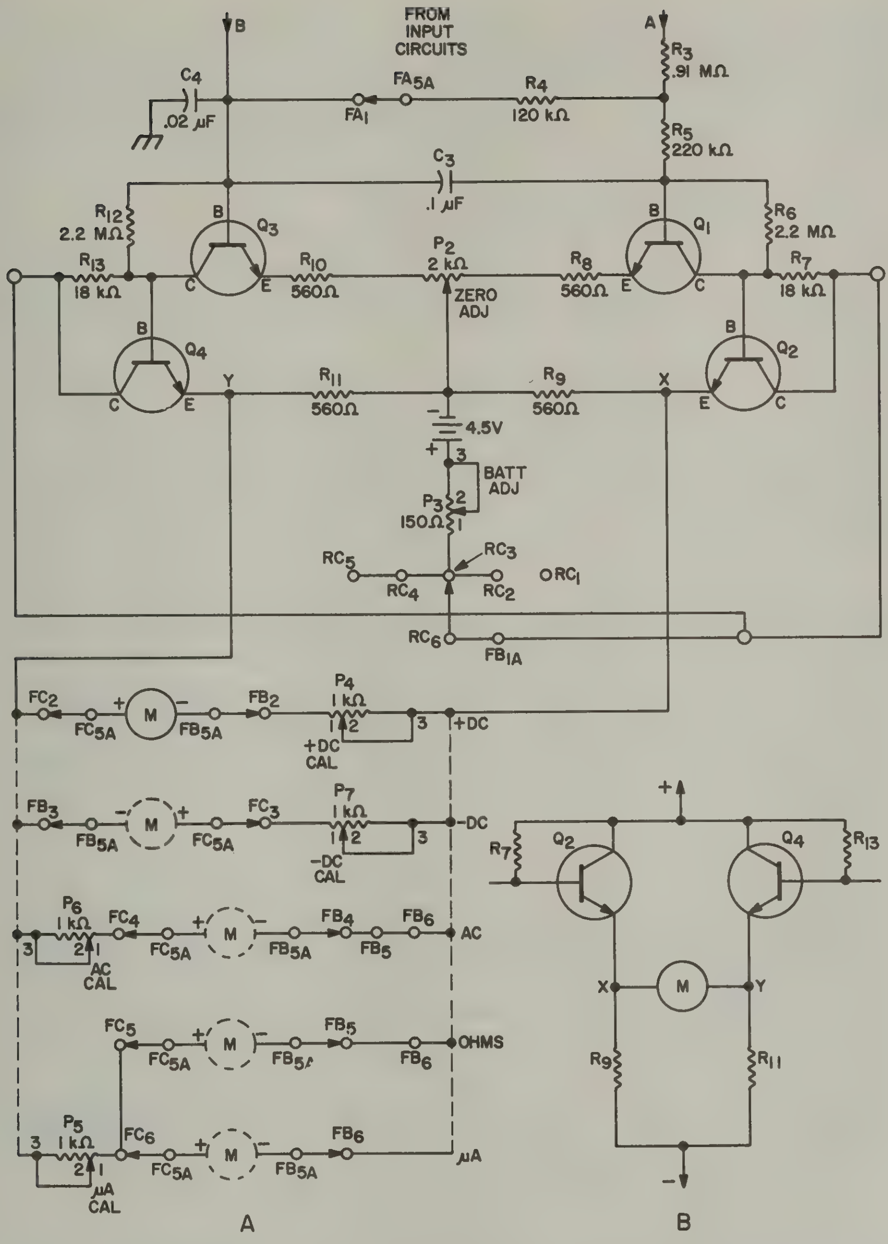


Figure 7

meter is used for ac measurements. This provides a shielding effect and prevents erratic readings caused by stray signals. Current limiting resistor R_5 prevents overloading of Q_1 and Q_3, and also reduces the loading effects of the transistors on the input circuit. Capacitor C_3 filters any pulsating dc input signals. Resistors R_6 and R_{12} stabilize the operation of Q_1 and Q_3 by providing negative feedback which reduces the gain and increases the input impedance of each transistor. Resistors R_8 and R_{10} provide additional stabilization and further increase the circuit input impedance. ZERO ADJUST control P_2 is adjusted to obtain exact balance in the amplifier circuits. It is set to position the meter pointer exactly over zero on the meter scale when no signal is applied. Resistors R_7 and R_{13} are the collector load resistors for Q_1 and Q_3, respectively. R_9 and R_{11} are emitter load resistors for Q_2 and Q_4, respectively. The output to the meter movement is developed across these two resistors. There is only one meter movement in the DeVry TRVM. The dashed meter movements in Figure 7A are shown only as an aid to understanding the operation of the TRVM.

Assume that a dc voltage is being measured which makes point A more positive than point B, in Figure 7A. When point A is more positive than point B, Q_1 base current increases and Q_3 base current decreases. Q_1 collector current then increases and Q_3 collector current decreases. These collector current changes cause corresponding changes in the voltages across R_7 and R_{13}. These voltages serve as the input signals for transistors Q_2 and Q_4. In turn, changes in Q_2 and Q_4 conduction provide the output of the differential amplifier.

When point A is more positive than point B, the increase in Q_1 collector current causes an increase in voltage across R_7 and a decrease in the voltage at the Q_1 collector. This also decreases the Q_2 base voltage because the base of Q_2 is connected to the collector of Q_1. The reduced voltage on the Q_2 base reduces the conduction of Q_2. This reduction of Q_2 emitter current reduces the voltage across R_9, which makes the voltage at point X of Figure 7A less positive.

When the input voltage (between points A and B) increases the forward bias of Q_1, it also decreases the forward bias of Q_3. With less forward bias, Q_3 conduction decreases, resulting in an increase in the voltage at the Q_3 collector. Because the base of Q_4 is connected to the Q_3 collector, the increase in Q_3 collector voltage also increases conduction of Q_4, which increases the voltage across R_{11}, making point Y more positive. Because the meter movement is connected between points X and Y, the difference in voltage between these two points will cause current in the meter movement and result in the desired pointer deflection.

Figure 7B shows just a part of the second stage of the differential amplifier, with the meter movement connected between points X and Y. This circuit is redrawn to show the similarity to the transistorized bridge circuit of Figure 3C. Any difference in Q_2 and Q_4 emitter currents produces a difference in potential between points X and Y, which causes meter current.

Although transistors Q_2 and Q_4 are directly controlled by the first stage transistors (Q_1 and Q_3), the basic bridge circuit is still formed as shown in Figure 7B. However, resistors R_7 and R_{13} serve as collector load resistors for the first stage transistors instead of being used as independent biasing resistors. Also, an input signal is applied to each transistor instead of just one. The circuit shown in Figure 7A also permits the meter to indicate zero when the input voltage is zero. This condition is not possible when only the simplified bridge circuit of Figure 3C is used.

The circuit action just described occurs whenever a positive dc voltage, ac voltage or resistance is measured by the meter. A negative dc input signal (point A more negative than point B) causes an opposite effect, with meter current from points Y to X.

The lower portion of Figure 7A shows variable resistors connected in series with the meter movement. These resistors and the polarity of the meter movement are selected by the FUNCTION switch. The variable resistors are adjusted to obtain proper calibration of the meter for each function. This is done by reducing current through the meter movement until deflection of the pointer corresponds to the value of the measured calibration voltage, current or resistance. The vertical dashed lines of Figure 7A show the connections at different FUNCTION switch positions.

The differential amplifier of the transistorized meter isolates the meter movement from the input signal. This protects the meter movement from being damaged by excessive current. This is because the resistance values in the amplifier circuit are selected to limit current to quantities that are not much greater than saturation collector current of the transistors. This prevents the voltage difference across points X and Y from becoming great enough to cause damaging current through the meter movement. The input circuit resistors also serve as voltage dividers that limit the amplitudes of input signal voltages to safe values, in almost all situations.

Power Supply

The source of the current used to deflect the meter pointer is the amplifier power supply. The DeVry TRVM power supply consists of four flashlight cells: one C cell and three D cells. The D cells are used to supply the operating voltage and current for the transistor circuits. The single C cell is used as a constant voltage source when the TRVM is used to measure resistance.

The D cells are connected in series, for a total voltage of about 4.6 volts, when the cells are new. However, cells decrease in voltage as they are used. The transistor amplifier circuit can operate properly from about a 4-volt power source. This meter can therefore continue to use the supply batteries until the voltage drops to slightly less than 4 volts without affecting the meter accuracy.

Another example of the wide use of electronic meter techniques is the field strength meter shown above. This instrument measures the voltage induced into a test antenna by TV and FM stations.

Courtesy Sencore

A special circuit is used to accommodate the changing battery voltage. This circuit includes BATTERY ADJUST control P_3 shown in Figure 6. P_3, which is between the battery positive terminals and the amplifier circuit, is adjusted so that the voltage at the collectors of Q_2 and Q_4 is about 4 volts positive with respect to the negative battery terminal. This voltage is measured by the meter movement when the FUNCTION switch is at the BATT position. A special green mark at mid-scale on the meter's faceplate indicates the proper voltage. As the D cells age, the setting of P_3 can be changed to compensate for the gradual drop in battery voltage.

The single C cell is switched into the meter circuit whenever the meter is used to measure resistance. This battery supplies the current necessary to develop a signal for the meter amplifier when the FUNCTION switch is set to the OHMS position.

After making any measurements, you should turn the RANGE switch to the OFF position. In this way, you extend the life of the batteries. Since there are no tube heaters or other circuit elements that require any warm-up, the TRVM is ready to operate as soon as it is turned on.

Input Circuits

The TRVM has both FUNCTION and RANGE switches. The settings of these two switches determine the type of measurement made and the amount of input signal required to obtain full-scale meter deflection.

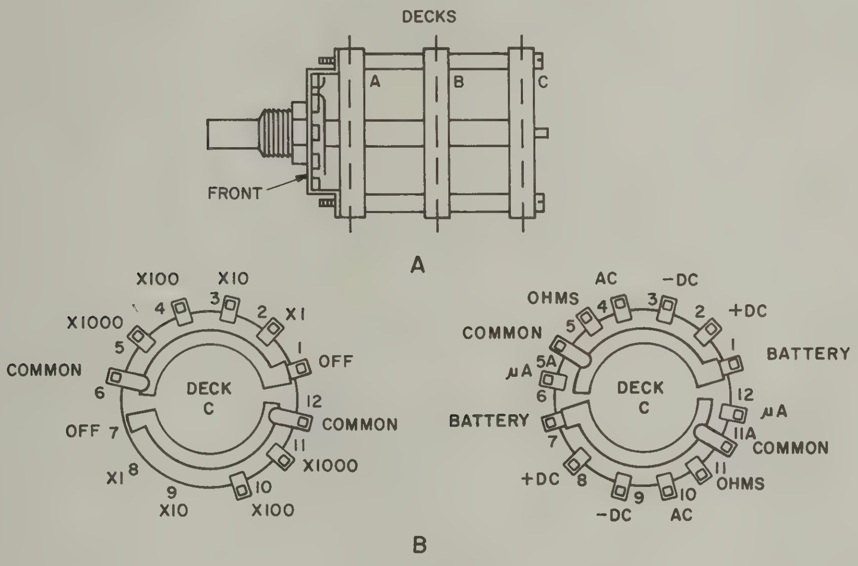


Figure 8

Figure 8A shows the construction of the RANGE and FUNCTION switches. They are multi-position, multi-deck switches. Figure 8B shows the function and range position relationships of the switches with respect to the contact arrangements on the switch rear decks, as viewed from the rear of the switches. The RANGE switch is shown on the left, and the FUNCTION switch on the right. Each terminal is labeled according to its operation.

The RANGE switch is a two-section, five-position switch. As shown in Figure 8B, it has two rear deck wiper terminals (6 and 12) which ride continuously on the rotating contacts. These points are labeled COMMON in Figure 8B. Terminals 8 and 9 are not used. The FUNCTION switch is a two-section, six-position switch. Its common points are terminals 5A and 11A. Each rotating contactor has an extended point or tab which connects to stationary contact points around the switch deck as the shaft is rotated.

These tabs connect the different circuits to the amplifier and meter movement.

The labeling of the switch contacts of each control shown in Figure 6 is as follows: the first letter refers to control operation, F for FUNCTION or R for RANGE switch; the second letter refers to the deck; while the following number (a letter may also appear) refers to the terminal.

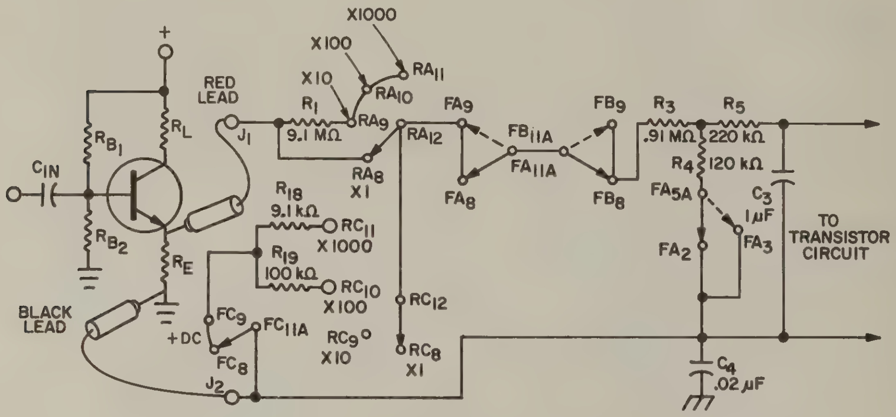


Figure 9

A simplified drawing of the dc input circuit of the TRVM is shown in Figure 9. This partial circuit is basically the same for both +DC and −DC function switch settings. The FUNCTION switch is set at +DC and the RANGE switch is set at ×1. The meter is being used to measure the emitter-to-ground voltage of a transistor amplifier. This voltage is applied to J_1 and J_2, with J_1 more positive than J_2. With this RANGE switch setting, the dc input to J_1 is applied directly to resistors R_3 and R_4 between the input jacks, and the input to J_2 goes directly to the base of transistor Q_3.

When the RANGE switch is set at ×10, R_1 is connected into the input circuit in series with R_3 and R_4. The dc test input voltage is then divided between R_1, R_3 and R_4. The voltage across R_4 is the dc signal applied to the transistor circuit through R_5 and across C_3.

When the RANGE switch is set at ×100, resistors R_{19} and R_1 are connected across the meter input. The series combination of R_3 and R_4 is then in parallel with R_{19}, which causes more of the input voltage to be dropped across R_1. Again, the voltage across C_3 is applied to the transistor circuit.

When the RANGE switch is set at ×1000, R_{18} is connected into the circuit in place of R_{19}. Now, even more of the input voltage is dropped across R_1. Each RANGE switch resistor has a 1% tolerance, which makes the voltage readings very accurate for any RANGE switch setting.

A dc signal must be applied to the transistor base circuit regardless of the type of measurement being made. Therefore, to measure an ac test voltage, the input circuits must have some means of changing the ac voltage to dc. To do this, a rectifier is connected in the input circuits. When an ac voltage is applied to the input jacks, the rectifier circuit produces a dc voltage which is effectively equal to the peak value of the applied ac voltage.

Figure 10 shows a simplified schematic diagram of the ac input circuit for the TRVM shown in Figure 6. Assume that an ac voltage is being measured. With the FUNCTION switch set at AC and the RANGE switch set at ×10, the ac voltage being measured is applied to input jacks J_1 and J_2. Capacitor C_1 at the J_1 input has a relatively low reactance at the frequencies normally measured, so that most of the ac signal voltage appears across R_{14}, R_{15}, R_{16} and R_{17}. These resistors act as a voltage divider, reducing the ac voltage applied to the rectifier circuit.

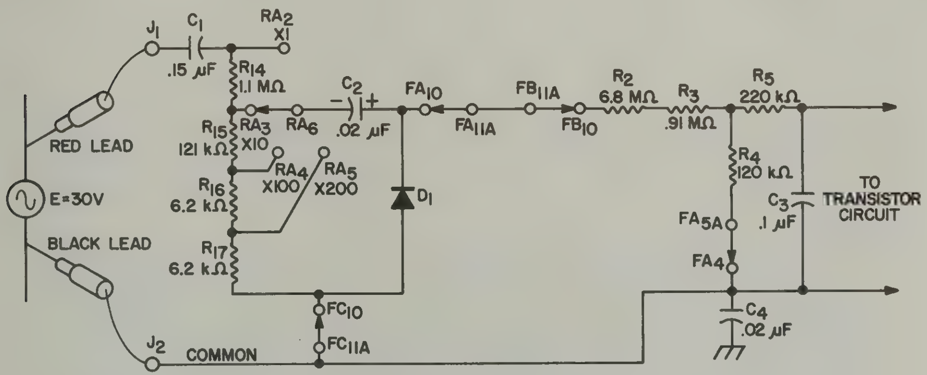


Figure 10

Diode D_1 conducts when the input signal makes J_2 positive with respect to J_1. Current is from J_1 through C_1 and R_{14}, through the RANGE switch (RA_3 and RA_6), through C_2, and D_1 (cathode to anode), and through the FUNCTION switch (FC_{10} and FC_{11A}) to J_2. When D_1 conducts, its low forward-biased resistance allows C_2 to charge to the approximate peak value of the ac voltage across switch contacts RA_6 and FC_{10}. The polarity of this charge is shown in Figure 10. Capacitor C_2 has a high-resistance discharge path when D_1 is not conducting, so that C_2 remains almost completely charged, and D_1 conducts very little after the first few negative alternations of the ac input signal.

During the alternations when J_1 is more positive than J_2, the positive signal at J_1 adds to the charge on C_2. This half-wave rectified positive dc voltage at the junction of C_2 and D_1 is applied through the FUNCTION switch (FA_{10}, FA_{11A}, FB_{11A} and FB_{10}) to resistors R_2, R_3 and R_4. This voltage also charges capacitor C_3 through R_5. The resultant charge, voltage filtered by C_3, causes signal current in the base circuits of transistors Q_1 and Q_3.

To measure resistance, the TRVM FUNCTION switch is set to OHMS, and the OHMS ADJUST control is used to zero the meter pointer. With this meter set to measure resistance, a 1.5-volt C cell is connected into the meter input circuit. Depending on the RANGE switch setting, the C cell is connected to one of the resistors R_{20} to R_{23} on deck B of the RANGE switch. These resistors are connected into the input circuits for different ranges of resistance measurements.

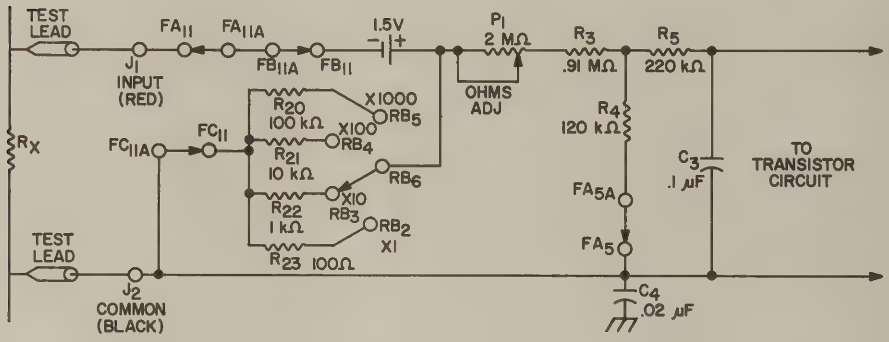


Figure 11

Figure 11 shows a simplified diagram of the OHMS input circuit for the TRVM of Figure 6. Assume that you are measuring an unknown resistance and the RANGE switch is set at ×10. When the unknown resistance, R_X, is connected between input jacks J_1 and J_2, a complete series circuit is formed from the negative terminal of the 1.5-volt C cell, through switch contacts FA_{11} and FA_{11A}, through J_1 and R_X, through J_2, the FUNCTION switch (FC_{11A} and FC_{11}), R_{22}, and the RANGE switch (RB_3 and RB_6) to the positive terminal of the C cell. Part of the C cell voltage is across R_X, and the rest of the voltage is across R_{22}. The voltage across R_{22} causes current through P_1, the OHMS ADJUST control, and resistors R_3 and R_4. In turn, the voltage across R_4 charges C_3 through R_5 to supply a signal to the transistor circuit.

The amount of pointer deflection depends on the ratio of the voltage drops across the unknown resistance, R_X, and the range resistor. If the unknown resistance is small compared to the ohms range resistor, the largest portion of the voltage is across the range resistor. This results in more signal to the amplifier and more current through the meter movement. This causes a large deflection of the meter pointer. If the unknown resistance is large, there is only a small portion of the voltage across the ohms range resistor, and the meter pointer does not deflect as far. The OHMS scale on the meter faceplate is for a SERIES OHMMETER, with zero ohms at the right end of the scale. This means that a reading of zero ohms will cause maximum deflection of the meter pointer, and reading of infinite resistance will cause no meter pointer deflection.

The general purpose TRVM shown in Figure 6 measures direct current in the microampere range without special equipment. For example, the TRVM can be used to measure the base, emitter or collector current of a transistor amplifier in a radio receiver. The TRVM does this by measuring the small voltage drop across low-resistance, high-precision resistors placed in SERIES with a test circuit. Test circuit current, passing through one of these precision resistors, causes a small voltage to appear across it. These special resistors are in the meter and are selected by the RANGE switch.

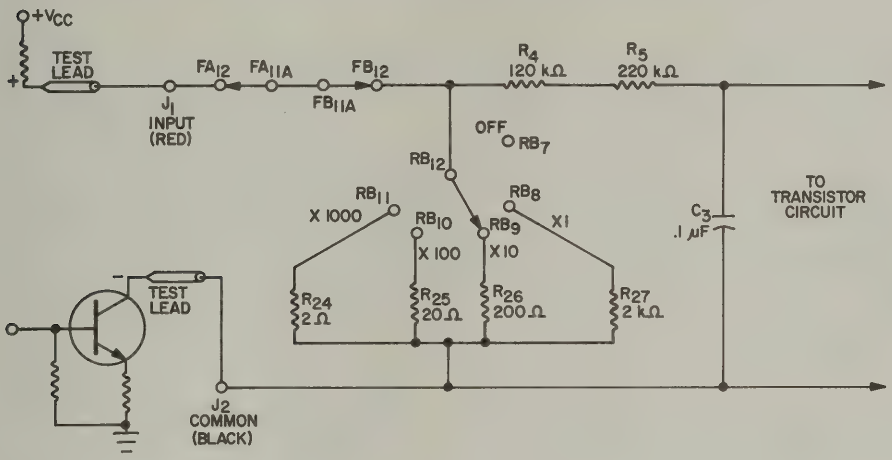
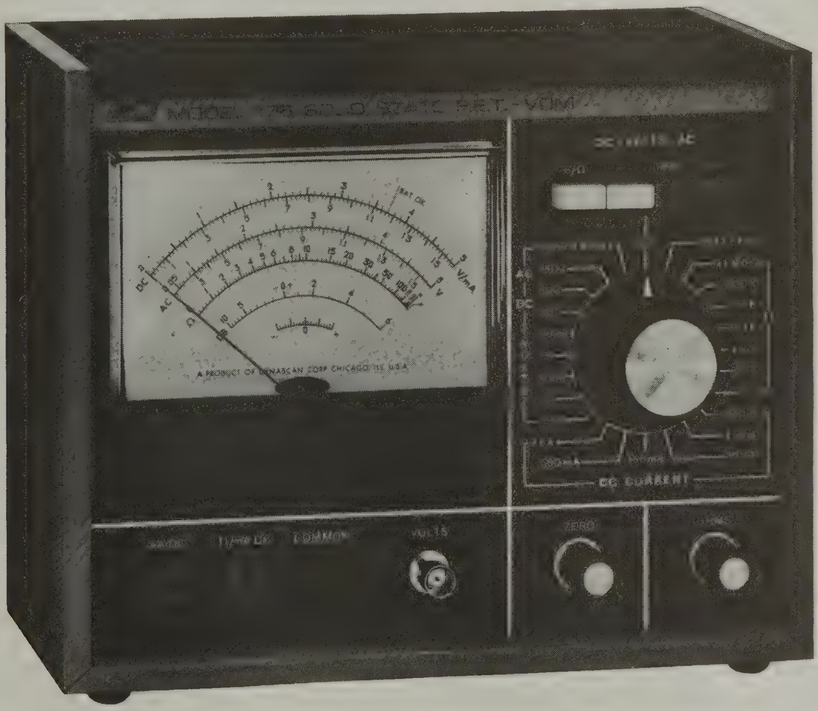


Figure 12

To measure current, the FUNCTION switch is set to the µA position. In this FUNCTION switch setting, one of the resistors of deck B on the RANGE switch (R_{24} to R_{27}) is connected into the input circuits as shown in Figure 12.



Transistorized electronic meters permit operation away from the power lines. The unit shown above employs field effect transistors to obtain a high input impedance.
Courtesy Dynascan Corp.

Which resistor is selected depends on the setting of the RANGE switch. For proper meter pointer deflection, input jack J_2 must be connected to a less positive point than input jack J_1. There is a complete current path from J_2 through one of the current range resistors to J_1 and the circuit being tested.

Figure 12 shows the direct current input circuit with the FUNCTION switch set at μA and the RANGE switch set at ×10. Assume that the test leads are inserted in series with the collector circuit of a transistor amplifier for a collector current measurement. The direct current range resistors are in series with the circuit under test. Test circuit current is from J_2 through R_{26}, through the RANGE switch (RB_9 and RB_{12}), and the FUNCTION switch FB_{12}, FB_{11A}, FA_{11A} and FA_{12}), to J_1 and back to the circuit under test. The amount of current through R_{26} determines the voltage drop across R_{26}, and this voltage is the signal applied to the transistor circuits. The resulting transistor base current is amplified and causes the meter pointer to deflect.

Operating the Meter

The complete TRVM circuit of Figure 6 is contained in a compact case for easy handling and portability. The external appearance of any commercial meter depends on what the manufacturer feels is the best design for its intended uses. The control locations may vary, and the controls may differ in size and shape.

The meter movement of the DeVry TRVM described in this lesson is mounted on the upper half of the front panel. The FUNCTION and RANGE switches are located below the meter movement. The ZERO ADJUST control and OHMS ADJUST control are mounted between the meter movement and the RANGE and FUNCTION switches.

The OHMS ADJUST control varies the pointer position at the right side of the meter scale when resistances are measured. It is adjusted to make the pointer rest over the zero mark at the right end of the OHMS scale when the test prods are touched together (zero resistance). The ZERO ADJUST control varies the pointer position on the left side of the meter scale. Before any measurements are made, the ZERO ADJUST control is positioned so that the pointer rests over the zero marks at the left end of the meter scales.

The RANGE switch determines the amount of signal applied to the amplifier and meter movement. It also serves as the on-off switch. When the RANGE switch is in its maximum counterclockwise position, the transistor circuits are disconnected from the meter circuit. At any other setting, the input voltage divider is connected to the meter circuits. The FUNCTION switch changes the internal meter circuits to allow the meter to measure the +dc or −dc voltage, ac voltage resistance, or direct current. To measure direct current, the FUNCTION switch is set at its maximum clockwise position. In the fully counterclockwise position, the meter can check the TRVM's power supply.

The input jacks are located below the RANGE and FUNCTION switches. Only one set of input jacks is used in this meter, making it unnecessary to change the test leads to different jack positions with every different type of measurement.

This general purpose DeVry TRVM uses different color-coded meter scales. The color of the labeling at each FUNCTION switch setting is the same color as the associated meter scale. This feature reduces chances of your reading the wrong scale for a particular measurement.

The DeVry TRVM has five scales. The green OHMS scale at the top is a nonlinear scale which begins with 0 on the right and ends with ∞ on the left. The major divisions are spaced closer together on the left side of the scale than on the right. The black DC VOLTS scale is a linear scale and is used to measure the +dc and −dc voltages. The scale divisions are equally spaced and start at the left with 0 and end at the right with 1.0. The DC μA scale, used to measure direct currents, starts at the left with 0 and ends at the right with 50. A red nonlinear scale, under the direct current scale, is used to measure ac voltages. The ac voltage scale extends from 0 at the left to 5 at the right and is labeled AC VOLTS. Below the ac scale is the dc **GALVANOMETER** scale. When the ZERO ADJUST control is used to position the meter pointer over zero on this galvanometer scale, this becomes a direct current scale with a deflection of 25 μA to either side of zero center. It is used with the FUNCTION switch set to μA.

A green rectangle on the meter face, labeled BATT ADJ, aids in setting the battery supply voltage to the proper value for the amplifier circuit. When the FUNCTION switch is set at BATT and the RANGE switch is any × position, the meter pointer should deflect to the rectangle of the battery adjust scale. Adjustment is made by varying the BATT ADJ control at the rear of the instrument. When you make this adjustment, be sure to position the pointer at the center of the rectangle.

The DeVry TRVM also has controls which are used to calibrate the instrument. The calibration controls are located inside the rear of the case and are adjusted through holes in the case. Calibration is accomplished by applying a known signal to the meter inputs and adjusting the associated calibration control until the meter pointer rests over the scale value equal to the known input. Figure 13 shows the location of these controls.

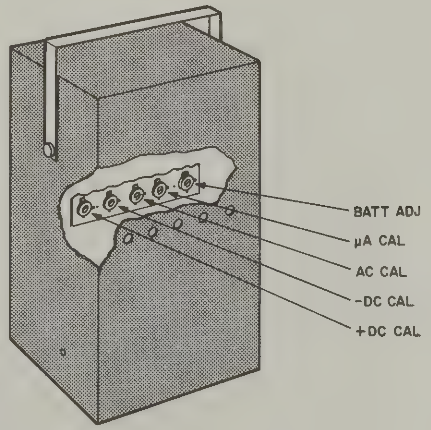


Figure 13

When the FUNCTION switch is set for a particular function, an associated calibration control is placed in series with the meter movement. These controls are variable resistors which adjust the meter pointer setting by changing the resistance offered to the current in the meter movement. The electrical connections of the calibration control are shown in Figures 6 and 7A. An alignment tool or a narrow-bladed screwdriver can be used to adjust the calibration controls.

When compensating for changes in battery voltage, it is not necessary to apply an external signal to the meter input. By turning the FUNCTION switch to BATT, the dc voltage at the BATT ADJ control, P_3, is applied to the transistors. Figure 14 shows that this voltage also causes current through R_{28} (a 7870 ohm resistor) and the meter movement. Since the meter movement requires 1 mA for full-scale deflection, .5 mA through the movement causes half-scale deflection. Multiplying 7870 ohms by .5 mA, we find that approximately 4 volts (3.935 volts, to be exact) produces half-scale deflection. Deflection to the center of the green area of the meter face (BATT ADJ) corresponds to this voltage. Therefore, the BATT ADJ control should be adjusted until the meter pointer rests at mid scale in the green area.

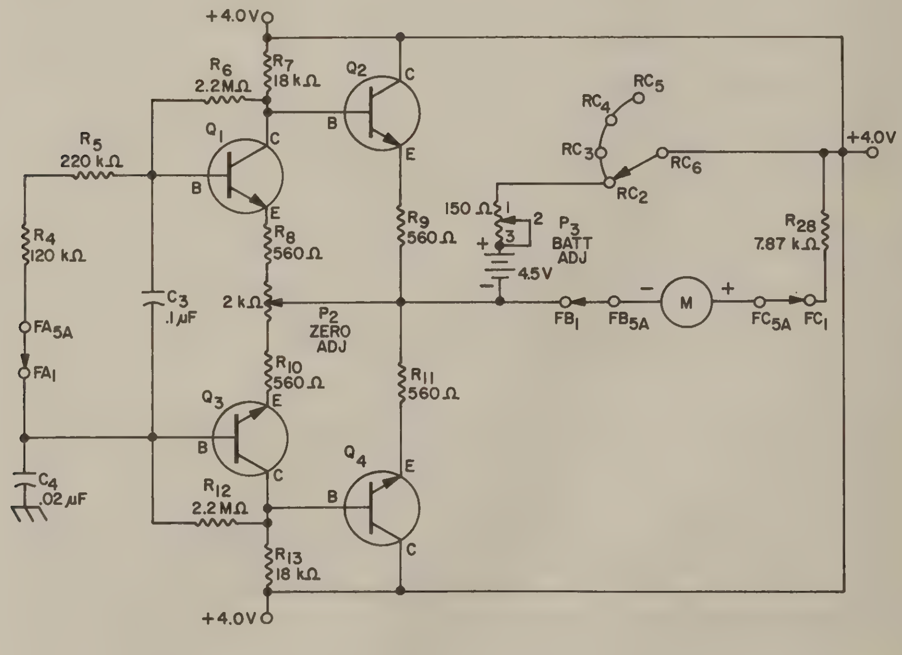


Figure 14

ACCESSORY EQUIPMENT FOR ELECTRONIC METERS

The DeVry TRVM and most other general purpose electronic meters may be used with various accessories which can increase the measuring capability of these instruments. The most common accessories are cable assemblies, probes and shunts. Cable assemblies come in many different lengths and

The following Practice Exercise questions cover the subjects which you have just studied. They are:

GENERAL PURPOSE TRANSISTORIZED VOLTMETER

METER AMPLIFIER AND METER MOVEMENT

POWER SUPPLY

INPUT CIRCUITS

OPERATING THE METER

13. In Figure 6, the base-to-emitter bias of each transistor determines the amount of current through each transistor in the differential amplifier circuit. True or False?

14. Figure 3C shows a bridge circuit where only one arm changes value to produce unbalance. Is this also true of Figure 7B?

15. In Figure 7A, the voltage supplied to the TRVM transistors is controlled by the setting of P_3. What is the advantage of this?

16. Why is it possible to operate the TRVM as soon as it is turned on?

17. How is the signal applied to the transistor circuits made smaller when the TRVM is switched from the ×1 DCV range to the ×10 range?

18. The TRVM effectively measures a dc voltage proportional to the peak value of an ac test voltage that is applied at the proper meter input jacks. True or False?

19. When the TRVM of Figure 6 is used to measure an ac test voltage, capacitor C_3 acts as a filter capacitor to remove the ripple in the rectified signal. True or False?

20. What is the operating principle for the resistance-measuring circuit of the TRVM?

21. How does the TRVM measure direct current?

22. How do the calibration controls change the deflection of a meter pointer?

have many types and combinations of terminal devices (for example, banana plugs or alligator clips). For working in high-frequency circuits, the cable assemblies are shielded. Probes are devices which can be added to the meter inputs to extend the instrument's normal operating range.

Figure 15A shows the simplest meter probe, the resistance probe. Resistance probes can be used to extend the voltage range of a voltmeter. If an electronic meter has an input impedance of 10 megohms, a resistance of 990 megohms is used in a test probe to extend the measuring range 100 times. This resistance is connected in series with the input circuit.

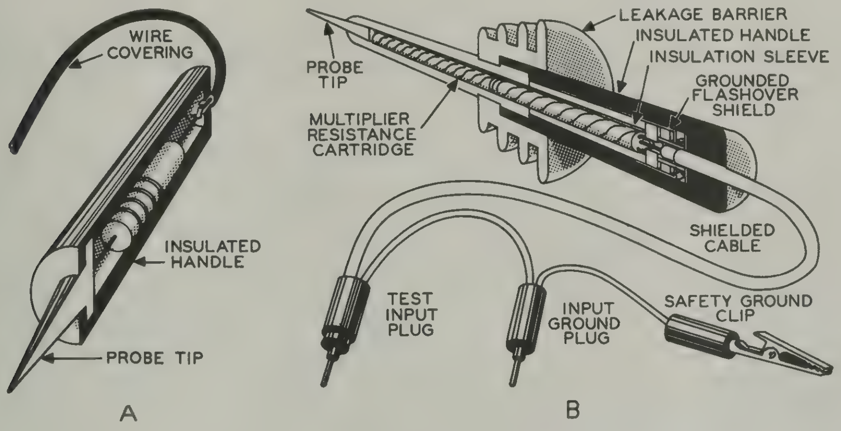


Figure 15

Resistances as high as 12,000 megohms may be used in test probes designed for high voltage use. High-voltage probes are usually longer than other resistance probes. They are constructed with a long exterior leakage path, to prevent arcing of high voltages from the circuit being tested, which could result in possible shock to the user. A typical high-voltage probe is shown in Figure 15B. Notice the special construction used to insure safety to the user. The probe is applied to the high-voltage point after the probe's plugs are inserted into the meter and the safety ground clip is fastened to a common, or grounded portion of the circuit being tested.

Diode probes are used to rectify high-frequency signals before they are fed through the cable to the meter input. This prevents signal losses that would occur if the high frequencies were passed through a long cable. Figure 16 shows a typical diode probe. Here, a solid-state diode is used in the test probe. The probe is applied to the ac test signal after the ground clip has been connected to the test circuit. When the signal at the anode is positive, effectively no signal is applied to the meter. When the anode is made negative, a signal equal to the voltage from ground to the diode cathode is applied to the meter. By using rectifier probes, a dc voltmeter can be used to

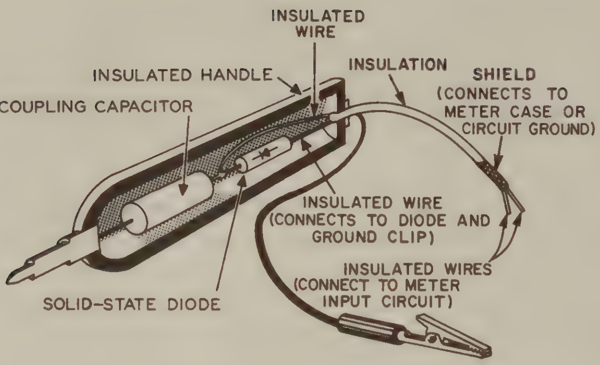

INSULATED WIRE
INSULATED HANDLE
INSULATION
SHIELD (CONNECTS TO METER CASE OR CIRCUIT GROUND)
COUPLING CAPACITOR
INSULATED WIRE (CONNECTS TO DIODE AND GROUND CLIP)
INSULATED WIRES (CONNECT TO METER INPUT CIRCUIT)
SOLID-STATE DIODE

Figure 16

measure ac voltages. However, you should not exceed the voltage rating of the probe when making measurements.

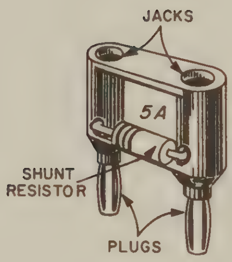


Figure 17

It is possible to extend the current measuring range of the TRVM of Figure 6 by means of external shunt resistors. By means of these shunts, currents of up to 5 amperes may safely be measured by the meter. This greatly extends the usefulness of any TRVM. The shunt is placed in parallel with the input circuit. A current shunt is shown in Figure 17. The shunt is made from a connector which has two plugs on one end and two jacks on the other end. The plugs and jacks are connected together so that a signal appearing at the plugs will also appear at the jacks. By connecting an external resistor across the plugs as shown, a current shunt is produced. To use the shunt, the test leads must first be removed from the meter. Then, the shunt is plugged into the meter jacks and the test leads are plugged into the shunt. This automatically places the shunt resistance across the input circuit.

THE DIGITAL MULTIMETER

The TRVM previously described represents one of the most commonly used meters for performing general electrical or electronic repairs. However, in recent years another type of electronic measuring instrument has become increasingly popular. This instrument is commonly referred to as a **DIGITAL MULTIMETER.** The digital multimeter performs the same basic functions as the transistorized meter; however, a different measurement technique is used and the results are displayed in a different way.

The digital multimeter may be referred to as a special type of electronic meter. Like the electronic meters discussed previously, the digital multimeter requires a power supply for operation. The digital multimeter also contains circuits which amplify and convert the measured voltage, current or resistance into a form suitable for display. However, the way in which the measured quantity is displayed is completely different. The digital multimeter displays the measured quantity as a group of individual numbers, or digits, instead of as a meter indication. By displaying the results as a group of digits, there is less chance for error. In other words, the operator is allowed to read the results directly in numerical form and is not required to interpret a meter indication.

Because operator errors are reduced and the measured quantity is expressed in digital form, greater measurement accuracy is obtained when using a digital multimeter. Also, since the digital multimeter uses all electronic components, its operation is inherently faster than that of the transistorized meter which uses a meter movement.

Basic Operation

A detailed analysis of a general purpose digital multimeter is not possible at this time because the device contains several types of circuits with which you are not yet familiar. However, a functional analysis of the instrument is possible.

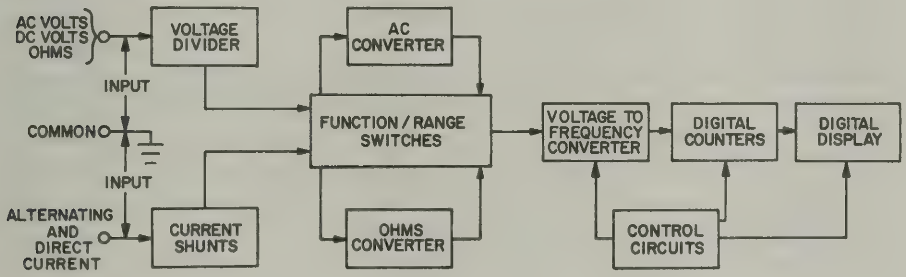


Figure 18

A simplified block diagram of a typical digital multimeter is shown in Figure 18. Notice that the multimeter has two inputs. When the multimeter is used to measure ac voltage, dc voltage, or resistance, one input is used; and, when alternating current or direct current is to be measured, the other input is used. The third input terminal serves as a common connection point.

The digital multimeter is equipped with FUNCTION and RANGE switches for the type of measurement to be made and for the range of values to be measured. These switches perform the same basic functions as the FUNCTION and RANGE switches used on the TRVM previously discussed.

Assume that the FUNCTION and RANGE switches are set so that the multimeter will measure dc voltages. The unknown dc voltage must first be applied to the proper input. The input voltage will then pass through a voltage divider or attenuator network which reduces the input voltage to a level which can be safely handled by the multimeter.

The dc voltage is then applied through the FUNCTION and RANGE switches directly to a voltage-to-frequency converter. The voltage-to-frequency converter changes the dc voltage into an ac signal which varies in frequency in proportion to the magnitude and polarity of the measured dc voltage. This output frequency is then applied to a group of digital counters which actually count and record the frequency in a very brief period of time.

The information stored in the digital counters is then applied to a digital display where the information is presented as a group of visual numbers which indicate the exact dc voltage that is being applied to the input terminals. The entire operation obviously requires precision timing, and in order for each circuit to perform its function at the right time, special control circuits are required. The control circuits also insure that each circuit has time to respond to its particular input signal.

If the multimeter is to be used to measure an ac voltage, the FUNCTION and RANGE switches must be appropriately set for this purpose. The ac voltage is first applied across the voltage divider where it is reduced to a convenient level. The signal is then applied to an ac converter where it is changed to a dc voltage that varies in proportion to the amplitude of the ac input. The dc output voltage is next applied to the voltage-to-frequency converter where it is changed to an ac signal frequency which is then counted and displayed. The displayed numbers correspond to the ac voltage at the input terminals.

When the multimeter is used to measure resistance, the FUNCTION and RANGE switches must be appropriately set for this purpose. The unknown resistance is connected to the same input terminals used to measure ac or dc voltages. However, in this mode of operation, the unknown resistance is connected to an ohms converter through a portion of the voltage divider. The ohms converter works in conjunction with the voltage divider to produce an output dc voltage which is proportional to the value of the unknown resistance. This dc voltage is then applied to the remaining circuits where it is processed in the same manner as before, and the numbers which appear on the digital display represent the value of the unknown resistor.

When the multimeter is used to measure either alternating or direct current, the appropriate input terminals must be used, as shown in Figure 18. The unknown current must pass through current shunts (resistors) which are selected by the RANGE switch. The input alternating or direct currents through these shunt resistors produce appropriate ac or dc voltages which then can be processed by the remaining circuits. If an alternating current is being measured, the FUNCTION switch must be appropriately set so that the ac voltage developed across the selected shunt resistor is applied to the ac converter. The output of the converter is then processed by the remaining circuits and the digital display presents a series of numbers which indicate the value of the input current.

If a direct current is being measured, the FUNCTION switch is set so that the dc voltage developed across the selected input shunt resistor is applied directly to the voltage-to-frequency converter. The signal is then processed in the same manner as before and the digital display presents a direct current reading.

The RANGE switches are actually used to select the voltage divider and current shunt components. The RANGE switch therefore insures that the input voltages and currents are reduced to levels which can be handled by the circuits in the multimeter. The FUNCTION switch insures that the appropriate input circuits are used to convert each input quantity into a dc voltage that corresponds to the value of the input quantity. This dc voltage is then processed by the remaining circuits and an appropriate digital readout is obtained.

Using the Digital Multimeter

The digital multimeter is extremely easy to operate. The device usually contains a minimum number of controls or switches, and because of the use of transistors and integrated circuits, it is usually quite small and light in weight. A typical digital voltmeter is shown in Figure 19. This device

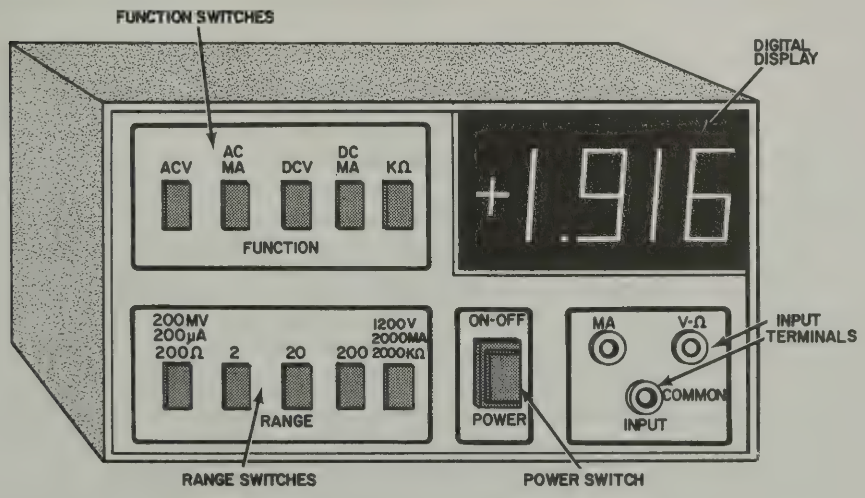


Figure 19

incorporates all of the circuitry shown in Figure 18, and it is representative of the compact and modern units currently in use.

The digital multimeter shown in Figure 19 requires 120-volt, 60-Hz power for operation. To activate the unit it is necessary only to depress the ON-OFF pushbutton POWER switch located on the front panel. If this switch were depressed again, the unit would be turned off.

The input terminals (actually test lead jacks) are also located on the front panel and are appropriately identified. The COMMON terminal serves as a common connection point for the other two input terminals. One input terminal is identified by the letters MA. This terminal and the COMMON terminal are used when measuring either an alternating or direct current. The letters MA (for milliamperes) are used since the multimeter measures current in milliamperes on all but one range. When voltages or resistances are to be measured, the V-Ω terminal and the COMMON terminal are used. A pair of red and black test leads are used to apply signals to the input terminals of the digital multimeter. When using the multimeter, it is therefore necessary to plug the two test leads into the appropriate terminals or test lead jacks.

The FUNCTION and RANGE switches are also located on the front panel. Five FUNCTION switches are used to select the type of measurement to be made. These switches are pushbutton types and only one can be activated at a time. Each time a new pushbutton is depressed, a previously depressed pushbutton will return to its original (off) position. For example, if an ac voltage must be measured, the ACV pushbutton must be depressed, or if a dc voltage must be measured, the DCV pushbutton must be depressed. When alternating or direct currents must be measured, the AC MA or DC MA pushbuttons must be depressed. When resistance must be measured, the KΩ pushbutton must be depressed.

The RANGE switches operate in the same manner as the FUNCTION switches. However, these pushbutton switches are used to determine the maximum voltage, current or resistance that can be measured by the multimeter. For example, if the 200 MV—200 μA—200Ω pushbutton is depressed, the multimeter cannot measure a voltage that is greater than 200 millivolts, a current greater than 200 microamperes, or a resistance greater than 200 ohms. If the switch which is identified by the number 2 is depressed, the maximum voltage, current or resistance to be measured cannot exceed 2 volts, 2 milliamperes or 2K ohms. The switches labeled 20 and 200 simply extend the maximum range of the multimeter even further. The 1200V—2000 MA—2000 KΩ switch establishes the maximum input levels which can be applied to the multimeter. With this switch depressed, the device will measure voltages as high as 1200 volts, currents as high as 2000 milliamperes (2 amperes), and a resistance as high as 2000K ohms.

The FUNCTION and RANGE switches must be used together to control the operation of the multimeter. For example, if you wanted to measure the 120-volt, 60-Hz ac voltage from a standard wall receptacle, you must first depress the ACV (FUNCTION) switch and the 200 (RANGE) switch. The multimeter would then display the number 120.0 if the voltage is exactly equal to 120 volts. As another example, assume that you wanted to measure the output voltage from a standard 1.5-volt flashlight cell. You would depress the DCV (FUNCTION) switch and the 2 (RANGE) switch. The negative side of the cell should then be connected to the COMMON terminal on the multimeter and the positive side of the cell to the V-Ω terminal on the meter. The multimeter should then indicate the exact voltage of the cell, and the polarity of the voltage with respect to the COMMON input terminal. A typical reading for a new battery would be +1.570 volts. If the leads to the cell were reversed, the multimeter would indicate a voltage of −1.570 volts, since the V-Ω terminal would be negative with respect to the COMMON terminal.

If you wished to measure a direct current of approximately 100 milliamperes, you would depress the DC MA (FUNCTION) switch and the 200 (RANGE) switch. The exact current value (up to 200 mA) would then be displayed when the measurement was taken. To measure a resistance of 100 ohms you would depress the KΩ (FUNCTION) switch and the 200Ω (RANGE) switch. The exact value of resistance (up to 200 ohms) would then be displayed.

When selecting the proper RANGE pushbutton, the same general rules should be followed as when using the TRVM or any other multimeter. Always select a range that you expect to measure. Of course, when the value of the quantity to be measured is unknown, you should start with the highest range and work your way down.

The digital multimeter shown in Figure 19 displays four digits, or individual numbers. Each of the three digits on the right side of the display (9, 1 and 6) can change to any number from 0 to 9. However, the digit on the left side of the display can only change to a 0 or a 1. A digital multimeter which is designed in this manner is commonly referred to as a three and one-half digit multimeter since one of the digits cannot change to all of the numbers from 0 to 9. The digital multimeter shown in Figure 19 is therefore capable of displaying a number as low as 0000 or a number as high as 1999. This means that the maximum number that can be displayed will always be less than the selected range. For example, when the 200 (RANGE) switch is selected, the multimeter can only display a maximum number of 199.9 and when 2 (RANGE) switch is selected, the maximum number is 1.999.

All four digits are always used and a decimal point is automatically placed between the appropriate numbers to correspond to the selected range. A plus or minus sign always appears at the left side of the display when measuring direct currents or voltages to indicate the polarity of the currents or voltages at the input terminals.

Like the TRVM, the digital multimeter has a high input impedance. A typical value of input impedance for a meter like the one shown in Figure 19 would be approximately 10 megohms. Most digital multimeters are also protected against high voltages which might be accidentally applied to the input terminals during normal use.

Digital multimeters may also be classified as portable test instruments since many of them are available with optional batteries. This is possible because of the low voltage and current requirements of the transistors and integrated circuits in the digital multimeters.

SUMMARY

Both electric and electronic meters are used to measure voltage, current and resistance. An electric meter used to measure these quantities loads the test circuit to a certain extent. This loading effect, caused by the meter, changes the test circuit operation and can result in incorrect measurements. The electronic meter was developed to overcome the disadvantages of loading the circuit under test.

An electronic meter has an amplifier and power supply in addition to the meter movement and input circuits.

The heart of the electric meter is the meter movement, which uses test circuit current to cause the pointer to deflect. In an electronic meter, the current for the meter movement is supplied by the amplifier and power supply sections. The amplifier in an electronic meter increases the meter input impedance, increases meter sensitivity, offers overload protection and makes it possible to measure a wider range of frequencies than can be measured by an electric meter.

The TRVM is a multi-purpose meter which may be used to measure more than one quantity. This device represents one of the most commonly used test instruments, since it is ideally suited for either shop or field repair work.

Many types of accessory equipment are available for use with meters. An important accessory is the meter probe. It contains an element used to isolate the meter from the test circuit, rectify an ac signal, or block a dc signal. Another very important meter accessory is the current shunt. These

The following Practice Exercise questions cover the subjects which you have just studied. They are:

ACCESSORY EQUIPMENT FOR ELECTRONIC METERS

THE DIGITAL MULTIMETER

BASIC OPERATION

USING THE DIGITAL MULTIMETER

23. What type of probe would you use with a meter having a 10 megohm input impedance to measure the voltage (about 25 kV dc) of the high-voltage rectifier section in a color TV receiver?

24. Why are current shunts commonly used?

25. What is the advantage of rectifying a high-frequency signal within the test probe instead of in the meter circuit?

26. One advantage in using the digital multimeter is that there is less chance of operator error. True or False?

27. The digital multimeter is equipped with FUNCTION and RANGE switches which perform the same basic functions as the FUNCTION and RANGE switches used on the TRVM. True or False?

28. When the digital multimeter shown in Figure 19 is used to measure a 10-volt ac signal, which RANGE and FUNCTION pushbuttons must be depressed?

29. When using the digital multimeter in Figure 19 to measure dc voltage, which input terminals are used?

30. If the digital multimeter displays the number −1.500 and the DCV (FUNCTION) and 2 (RANGE) pushbuttons are depressed, what is the value and polarity of the voltage being measured?

31. The digital multimeter shown in Figure 19 is commonly referred to as a (a) one and one-half digit multimeter, (b) two and one-half digit multimeter, (c) three and one-half digit multimeter, (d) four and one-half digit multimeter.

32. When the digital multimeter shown in Figure 19 is used to measure resistance, the unknown resistor must be connected to the (a) MA and COMMON terminals, (b) V-Ω and COMMON terminals, (c) MA and V-Ω terminals.

shunts extend the current ranges of meters such as the TRVM. The shunt places a current-dividing resistance in parallel with the input circuit.

The digital multimeter is a relatively new device which offers certain advantages over the more commonly used electronic meters such as the TRVM. The digital multimeter performs the same basic functions as the TRVM; however, the measurements are displayed in digital or numerical form instead of as a meter indication. The digital display makes the device easier to use and effectively reduces the number of operator errors.

IMPORTANT DEFINITIONS

BRIDGE CIRCUIT—A measuring circuit consisting of four arms, with a variable resistance or impedance in one or more of the arms. Any change in the variable arm causes the bridge to be unbalanced, and a resultant difference of potential can be used to operate a meter movement.

D'ARSONVAL METER MOVEMENT—A type of direct current meter movement in which a lightweight wire coil, supported on jewel bearings between the poles of a permanent magnet, is rotated by the effects of an electric current in the coil.

DIFFERENTIAL AMPLIFIER—In a transistorized meter, a circuit whose output signal is proportional to the difference in emitter current through two transistor amplifiers whose no-signal emitter currents cause the meter to read zero.

DIGITAL MULTIMETER—An electronic instrument that measures voltage, current and resistance and provides a digital (numerical) indication of the results.

ELECTRIC METER—A meter that consists simply of a meter movement and the input circuits necessary to measure various electrical quantities.

ELECTRONIC METER—A meter that includes vacuum tube or transistor circuits, with the necessary power supplies, in addition to the meter movement and input circuits of an electric meter.

FUNCTION SWITCH—In a multiple function meter, the switch that selects the proper circuitry for the type of measurement desired.

GALVANOMETER—An instrument for measuring a small electric current by movements of a magnetic needle or a coil in a magnetic field which indicates both the amount and direction of current through the meter.

INPUT IMPEDANCE—In an electronic meter, the total opposition offered to the test circuit current. The combined resistance and reactance of the input circuit and amplifier input.

INPUT RESISTANCE—In an electric meter, the total resistance offered to the test circuit current.

LOADING—The action of a meter using current from the circuit it is measuring.

MULTIPLIER—A resistor connected in series with the meter movement to increase the range of a voltmeter.

IMPORTANT DEFINITIONS (Continued)

RANGE RESISTOR—A general term used to describe a resistor used to increase the range of a meter.

RANGE SWITCH—In a multiple-range meter, the switch that selects the resistor or combination of resistors to give the desired range of readings.

SHUNT—A resistance connected in parallel with the meter movement or test circuit to effectively reduce the total resistance and increase the current measuring range of the meter.

TAUT-BAND METER MOVEMENT—A type of direct current meter movement similar to D'Arsonval movement except for the use of a metallic band to support the moving coil.

TRANSISTORIZED VOLTMETER (TRVM)—An electronic meter which uses a transistor amplifier to provide the current for the meter movement.

VACUUM TUBE VOLTMETER (VTVM)—An electronic meter which uses a vacuum tube amplifier to provide current for the meter movement. These meters are rapidly being replaced by transistorized voltmeters (TRVM's).

PRACTICE EXERCISE SOLUTIONS

1. Electric meters and electronic meters.

2. Both types use a meter movement and input circuits to extend the range of measurements the meter can make.

3. (b) less current from the test circuit.—The electronic meter uses only small current from a test circuit to develop a signal for the meter amplifier.

4. (b) the power supply and amplifier section.

5. True

6. (a) internal meter resistance.

7. True

8. When the same amount of voltage is applied to both branches of a bridge circuit whose branches have equal resistance, the current through these branches will be equal. This is referred to as balance in a bridge circuit.

9. (c) resistor.—The voltage drop across the transistor decreases or increases as the applied signal goes positive or negative.

10. Reference transistor Q_2 in Figure 3C is used to compensate for any change in the conduction of Q_1.

11. The ZERO ADJUST control is a variable resistor which is adjusted to make up for any small differences in the resistances of the circuit branches, so that a zero meter reading can be obtained with no input signal applied.

12. The power supply section of the electronic meter, since it furnishes the voltage and current for the operation of the bridge circuit.

13. True—The base-to-emitter bias on any transistor determines the amount of current through the transistor.

14. No—Both arms are active. As the current in one arm decreases in value, the current in the other arm increases in value.

15. The setting of P_3 allows greater usable cell life and reduces the number of times the cells must be changed while keeping the collector voltage of each transistor at about 4 volts.

16. Because there are no tube heaters or other circuit elements that require any warm-up time.

17. The signal to the transistor circuit is reduced because R_1 is now connected into a series circuit with R_3 and R_4. With an additional resistor in this

PRACTICE EXERCISE SOLUTIONS (Continued)

circuit, the voltage across R_4 is decreased and a smaller signal is passed to the transistors.

18. True

19. True

20. The TRVM resistance measuring circuit operates on the basic principle that a voltage divides between two series resistors in proportion to their resistance values. In this case, the voltage divides between a known and unknown resistance, and the voltage across the known resistance is the signal applied to the transistor amplifier of the meter.

21. The TRVM measures direct current by measuring the voltage dropped across precision low-resistance value resistors that are placed in series with the circuit being measured. This voltage is proportional to the current through the resistors.

22. The calibration controls are adjusted to change the resistance offered to current in the meter movement circuit.

23. A high-voltage resistance probe should be used. This probe would extend the range of the meter and would protect you because it would not break down or arc over.

24. Current shunts are simply external shunt resistors which are used to extend the current-measuring range of a meter.

25. By rectifying the high-frequency signal within the test probe, the high frequency does not have to pass through a long cable where considerable signal loss could occur.

26. True

27. True

28. The ACV (FUNCTION) pushbutton and the 20 (RANGE) pushbutton should be depressed.

29. When measuring dc voltage, the V-Ω and COMMON terminals must be used.

30. The measured voltage is a negative dc voltage with a value of 1.5 volts.

31. (c) three and one-half digit multimeter.

32. (b) V-Ω and COMMON terminals.

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7420A
EXAMINATION CHECK SHEET

1. C - THE PRIMARY ADVANTAGE OF AN ELECTRONIC VOLTMETER OVER AN ELECTRIC VOLTMETER IS ITS ABILITY -- TO DECREASE LOADING EFFECTS.
The high impedance input section and the high-gain amplifier section reduce circuit loading but do not completely eliminate it.

2. B - THE HIGH INPUT IMPEDANCE OF AN ELECTRONIC METER IS SUPPLIED BY -- THE INPUT AND AMPLIFIER SECTIONS.
The amplifier must have a high input impedance so that it does not load the high impedance input circuits.

3. B - WHEN THE INPUT SIGNAL GOES POSITIVE IN FIGURE 3C, -- THE VOLTAGE DROP ACROSS R_2 INCREASES.
As the input signal drives the base of Q_1 positive, Q_1 collector current increases, thus increasing the voltage drop across R_2. The current through Q_2 and the voltage drop across R_4 remain relatively constant.

4. C - IN THE CIRCUIT OF FIGURE 7A, IF POINT A IS MADE POSITIVE WITH RESPECT TO POINT B, -- Q_3 COLLECTOR CURRENT DECREASES.
Under these conditions, Q_1 collector current increases and Q_3 collector current decreases. This causes Q_2 collector current to decrease and Q_4 collector current to increase.

5. C - MOVING THE SLIDER ON P_2 TO THE LEFT IN FIGURE 7A -- INCREASES Q_3 BASE CURRENT.
Moving the slider on P_2 to the left reduces the Q_3 emitter resistance. This reduces the reverse bias developed by the emitter resistance and increases the Q_3 base current.

6. D - THE METER MOVEMENT OF THE TRVM IN FIGURE 6 MEASURES THE -- DIFFERENCE IN THE EMITTER VOLTAGES OF Q_2 AND Q_4.
The meter movement is connected between the emitters of Q_2 and Q_4 through the FUNCTION switch.

7. A - TO EXTEND THE HIGH-VOLTAGE RANGE OF A TRVM, A HIGH-VOLTAGE PROBE -- CONNECTS A HIGH VALUE RESISTANCE IN SERIES WITH THE METER.
The high value resistance forms a voltage divider with the meter's internal resistance, and reduces the voltage at the input terminals to a value that can be used by the meter.

8. A - WHEN THE DIGITAL MULTIMETER SHOWN IN FIGURE 19 IS USED TO MEASURE ALTERNATING CURRENT, WHICH INPUT TERMINALS MUST BE USED? -- THE MA AND COMMON TERMINALS.
The MA and COMMON terminals are used for both alternating current and direct current measurements, and the V-Ω and COMMON terminals are used for ac voltage, dc voltage and resistance measurements.

9. D - WHEN THE DIGITAL MULTIMETER SHOWN IN FIGURE 19 IS USED TO MEASURE A DC VOLTAGE OF APPROXIMATELY 100 VOLTS, WHICH RANGE SWITCH SHOULD BE DEPRESSED? -- THE 200 SWITCH.
The 200 (RANGE) switch allows for a maximum voltage measurement of 200 volts (actually 199.9 volts). The 100-volt input signal is well within this range and can be accurately measured.

10. C - WHEN THE ACV (FUNCTION) AND 2 (RANGE) SWITCHES ARE DEPRESSED, THE DIGITAL MULTIMETER SHOWN IN FIGURE 19 IS CAPABLE OF MEASURING -- AC VOLTAGES BELOW 2 VOLTS.
When activated, the ACV switch allows only ac voltages to be measured and the 2 switch allows the multimeter to measure ac voltages up to a maximum of 2 volts (actually 1.999 volts).

QUESTIONS

IMPORTANT—These instructions **MUST** be accurately followed to avoid loss, or errors in grading.

Indicate your answer on this sheet by filling in the box for the most correct answer to each question, as illustrated in the example below.

When all questions have been answered, place the answer card in the proper position to line up the boxes on the card with the boxes on the sheet.

Next, copy the complete lesson code into the space provided on the card, and fill in the answer boxes to correspond with those previously filled in on this sheet.

Before mailing, be certain your correct student number, name and address appear on the card.

LESSON CODE

7420A

Example: A fish is

A ☐ B ☐ C ☐ D ■

(A) a bird. (B) a mineral.
(C) a vegetable. (D) an animal.

1. A ☐ B ☐ C ☒ D ☐ **The primary advantage of an electronic voltmeter over an electric voltmeter is its ability**
(A) to increase loading effects. (B) to change, as much as possible, a circuit's operating conditions. (c) to decrease loading effects. (d) to produce changes in a circuit's operating conditions.

2. A ☐ B ☒ C ☐ D ☐ **The high input impedance of an electronic meter is supplied by**
(A) the FUNCTION switch. (B) the input and amplifier sections. (C) the meter movement. (D) the power supply.

3. A ☐ B ☒ C ☐ D ☐ **When the input signal goes positive in Figure 3C,**
(A) the voltage drop across R_2 decreases. (B) the voltage drop across R_2 increases. (C) the voltage drop across R_4 increases. (D) the voltage drop across R_4 decreases.

4. A ☐ B ☐ C ☒ D ☐ **In the circuit of Figure 7A, if point A is made positive with respect to point B,**
(A) Q_1 collector current decreases. (B) Q_2 collector current increases. (C) Q_3 collector current decreases. (D) Q_4 collector current decreases.

5. A ☐ B ☐ C ☒ D ☐ **Moving the slider on P_2 to the left in Figure 7A**
(A) increases Q_1 base current. (B) increases Q_4 collector current. (C) increases Q_3 base current. (D) decreases Q_2 base current.

6. A ☐ B ☐ C ☐ D ☒ **The meter movement of the TRVM in Figure 6 measures the**
(A) sum of the emitter voltages of Q_2 and Q_3. (B) collector voltages of Q_1 and Q_4. (C) base voltages of Q_1 and Q_4. (D) difference in the emitter voltages of Q_2 and Q_4.

7. A ☒ B ☐ C ☐ D ☐ **To extend the high-voltage range of a TRVM, a high-voltage probe**
(A) connects a high value resistance in series with the meter. (B) connects a high value resistance in shunt with the meter. (C) connects a low value resistance in shunt with the meter. (D) connects a low value resistance in series with the meter.

8. A ☒ B ☐ C ☐ D ☐ **When the digital multimeter shown in Figure 19 is used to measure alternating current, which input terminals must be used?**
(A) The MA and COMMON terminals. (B) the V-Ω and COMMON terminals. (C) the MA and V-Ω terminals. (D) Only the COMMON terminal.

9. A ☐ B ☐ C ☐ D ☒ **When the digital multimeter shown in Figure 19 is used to measure a dc voltage of approximately 100 volts, which RANGE switch should be depressed?**
(A) The 200 MV—200 μA—200Ω switch. (B) The 2 switch. (C) The 20 switch. (D) The 200 switch.

10. A ☐ B ☐ C ☒ D ☐ **When the ACV (FUNCTION) and 2 (RANGE) switches are depressed, the digital multimeter shown in Figure 19 is capable of measuring**
(A) alternating currents below 2 milliamperes. (B) ac voltages above 2 volts. (C) ac voltages below 2 volts. (D) dc voltages below 2 volts.

QUESTIONS

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(A) a bird. (B) a mineral.
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1. A ☐ B ☐ C ☒ D ☐

The primary advantage of an electronic voltmeter over an electric voltmeter is its ability
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When the input signal goes positive in Figure 3C,
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Moving the slider on P_2 to the left in Figure 7A
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When the digital multimeter shown in Figure 19 is used to measure a dc voltage of approximately 100 volts, which RANGE switch should be depressed?
(A) The 200 MV—200 μA—200Ω switch. (B) The 2 switch. (C) The 20 switch. (D) The 200 switch.

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When the ACV (FUNCTION) and 2 (RANGE) switches are depressed, the digital multimeter shown in Figure 19 is capable of measuring
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CATHODE RAY TUBES
AND
OSCILLOSCOPES

7425

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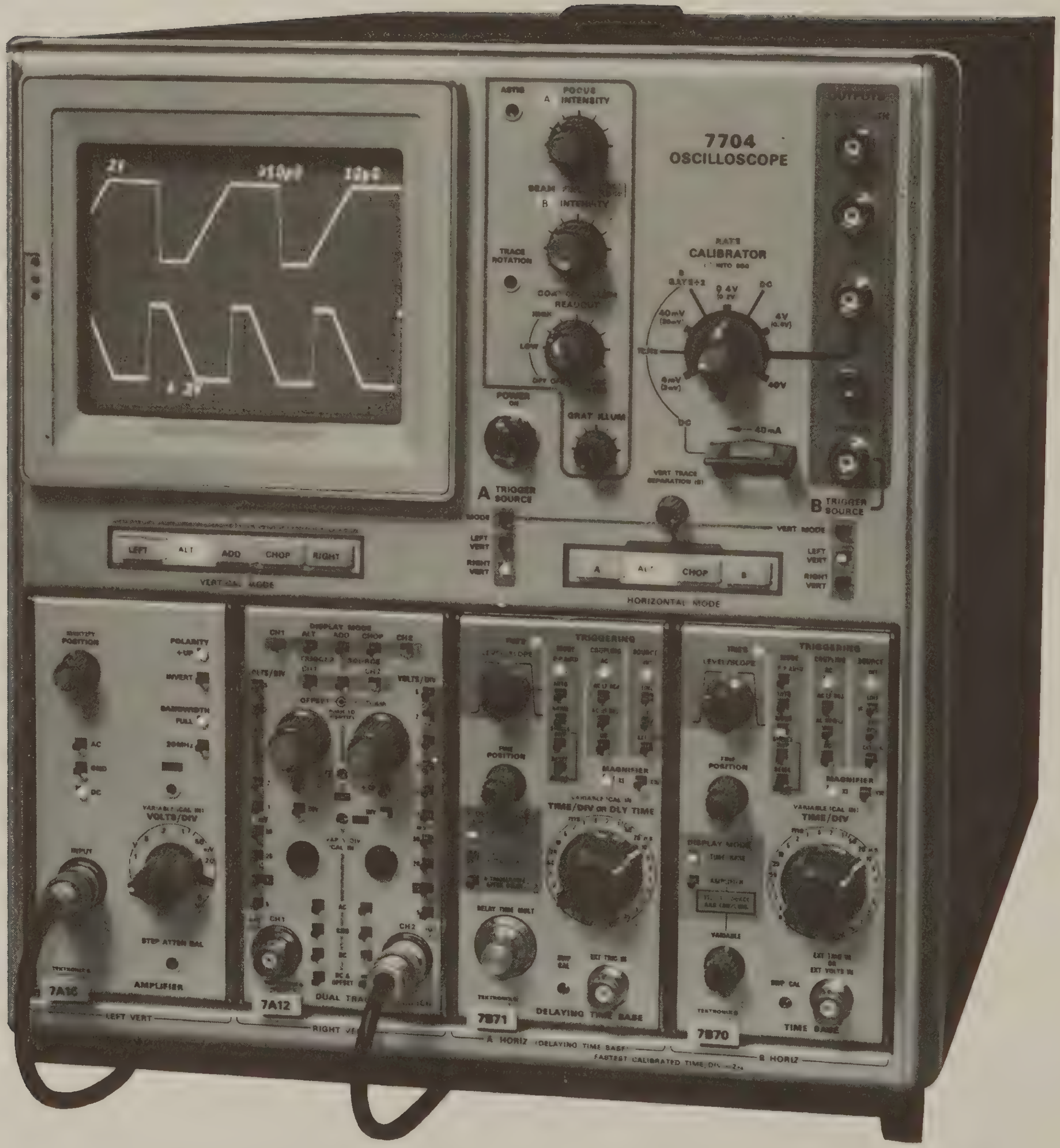

A high quality scope designed primarily for laboratory use. It features triggered sweep circuits, a calibrated time base and dual inputs for simultaneous viewing of two waveforms.

Courtesy Tektronix, Inc.

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It takes less time to do a thing
right than it does to explain
why you did it wrong.
—Henry Wadsworth Longfellow

CATHODE RAY TUBES AND OSCILLOSCOPES

Have you ever wondered about how a picture is formed on a television screen? Have you ever been puzzled about how an image is formed on a radar screen, or how voltage waveforms are displayed on the screen of an oscilloscope? These "pictures" are actually light images traced on the face of a special type of vacuum tube called a **CATHODE RAY TUBE (crt).** In this lesson, you will learn how the cathode ray tube operates and you will see how it is used in one of the most important electronic test instruments, the **CATHODE RAY OSCILLOSCOPE.**

The cathode ray tube develops a beam of electrons that is shaped and accelerated by high voltages which are developed within the instrument. The electron beam is transformed into visible light energy when it strikes a thin layer of phosphor material on the inside of the crt faceplate. The vertical and horizontal movement of the electron beam is controlled by the signals which are to be observed and by circuits in the oscilloscope.

The cathode ray oscilloscope is commonly referred to as an oscilloscope, or simply, as a "scope." The cathode ray tube is a vital part of the scope. The oscilloscope contains special circuits which control the operating voltages applied to the crt. The scope can be used to measure the amplitude, frequency or phase of ac voltages, the amplitude of dc voltages, and may also be used to observe the shapes of complex electronic waveforms. These capabilities make the oscilloscope valuable for waveform analysis, particularly in audio, television, transmitter and industrial applications.

GENERAL DESCRIPTION OF THE CATHODE RAY TUBE

Most general purpose oscilloscopes use cathode ray tubes designed for electrostatic focus and deflection. An electrostatically controlled crt has only a few elements, and its overall operation is easy to understand. The tube elements are usually mounted in a glass envelope, as in other tubes. Figure 1 shows a simplified diagram of a typical crt. Notice that this crt is divided into three sections: the electron gun, the deflection section and the screen. A beam of electrons from the gun passes between the deflection plates and strikes the screen, causing a spot of light on the screen.

The **ELECTRON GUN** is located in the neck of the crt, near the base of the tube envelope. The electron gun produces the beam of electrons and directs the electrons toward the screen. In many crt's, elements in the electron gun are used to focus the beam to produce a sharp image on the screen.

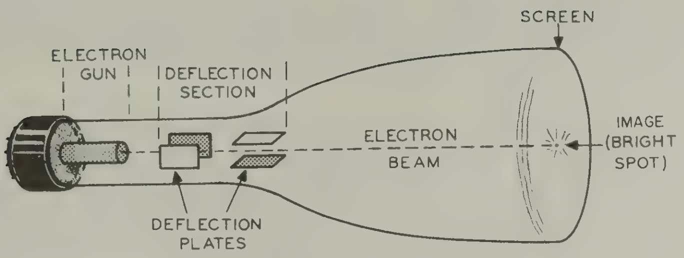


Figure 1

The deflection section is between the electron gun and the screen. In Figure 1, **DEFLECTION PLATES** are shown mounted inside the glass envelope. The electron beam can be bent, or deflected, by applying different voltages to the deflection plates. The voltages on the deflection plates attract or repel the electrons in the beam, causing the beam to move up or down and left or right, to trace out an image on the screen of the crt.

The **SCREEN** lies beyond the deflection section, on the inside of the viewing end of the glass envelope. It consists of a phosphor coating that gives off light when struck by fast-moving electrons. The screen lets you observe changes in the position and strength of the electron beam.

Electromagnetic lines of force may also be used to focus and deflect the electron beam in a crt. However, this technique is seldom used for crt's in oscilloscopes. The electromagnetic crt is advantageous when single frequency deflection voltages are used, and when a large deflection in a short distance is desirable. This is the situation in television receivers, where electromagnetic focus and deflection systems are commonly employed. The electromagnetic deflection system is also bulkier and heavier than the electrostatic system.

Another important reason for using an electrostatic crt in an oscilloscope is because simpler circuits can be used to produce the deflection signals. Also, since signals of many different frequencies are encountered, the deflection circuits must be capable of handling these frequencies, and electromagnetic deflection circuits cause distortion when used with wide bands of frequencies.

Since the electrostatic crt is by far the most popular type found in oscilloscopes, this lesson coverage will be limited to this type of crt.

CONSTRUCTION AND OPERATION OF THE CATHODE RAY TUBE

The construction of a crt is similar to that of many receiving tubes. In addition to holding the crt parts, the glass envelope maintains the vacuum necessary for proper tube operation. To understand the operation of the crt, it is necessary to study the functions of the major crt parts. Therefore, let's take a closer look at the parts shown in Figure 1.

The Electron Gun

The electron gun produces the beam of electrons that traces the pattern on the screen. The gun elements are made up of a heater, cathode, control grid, first anode and second anode, as shown in Figure 2. The operating voltages for these electrodes, received from the crt socket, are applied through the pins on the tube base.

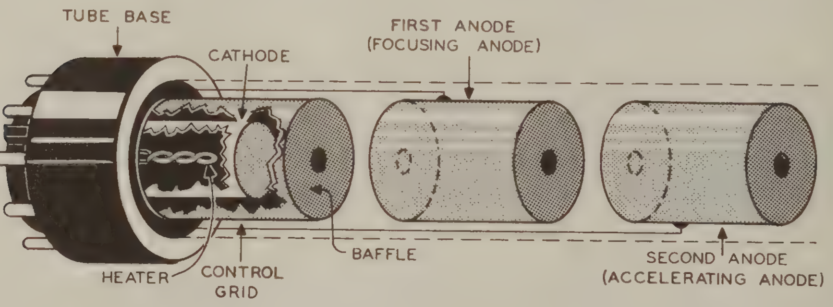


Figure 2

All of the gun electrodes except the heater are round tubes, or cylinders. The end of each cylinder is covered by a plate called a baffle. Holes in the centers of the control grid baffle, first anode baffle and second anode baffle lie along the center line, or axis, of the tube.

The heater, cathode and control grid have the same functions in the crt as they have in a regular triode vacuum tube. The heater raises the cathode temperature, and the heated cathode emits electrons. The potential between the control grid and cathode determines the brightness of the image on the crt screen by controlling the number of electrons that reach the screen.

High positive voltages are applied to the first and second anodes. The high potential on the **FIRST ANODE** attracts the electrons from the area near the control grid. The electrons are focused, or shaped into a beam, as they pass through the baffles between the first and second anodes. The focused beam of electrons is also speeded up, or accelerated, by the very high potential on the **SECOND ANODE.**

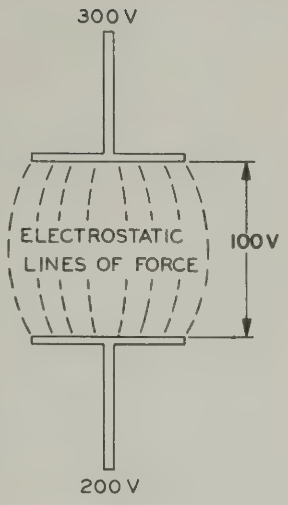


Figure 3

The electron beam is focused by an electrostatic field as shown in Figure 3. Here we see two plates having different potentials with respect to a common reference point. There is an electric field between the plates, made up of electrostatic lines of force. Notice how the lines of force near the edges of the charged plates bow out. The beam is focused by the electrostatic field that is caused by applying different potentials to the first and second anodes. Any electron passing through this field is influenced by the electrostatic lines of force. This is caused by a repelling effect between adjacent electrostatic lines of force.

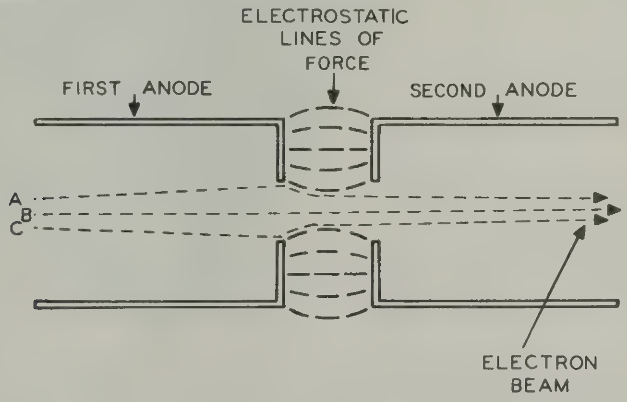


Figure 4

A cross-sectional view of the junction between the first and second anodes is shown in Figure 4. The electrostatic lines of force, caused by the difference of potential between the two anodes, is bowed out at the outer edges of the anodes and at the inner edges formed by the baffle holes.

As three electrons—A, B and C—pass through the hole in the first anode baffle on their way to the second anode, they are influenced by the lines of force. Because the electrons tend to follow the paths of the lines of force, electrons A and C are forced in toward the center. Since electron B is already traveling through the center, it is affected equally by the electrostatic lines above and below it, and it therefore remains in a straight line path.

As electrons A, B and C approach the more positive second anode, their speeds increase, and the lines of force then have less influence on the electrons. Therefore, electrons A and C continue to converge on electron B, and the three electrons move closer together as they travel from the second anode to the screen. At some specific point beyond the second anode, the three electrons will meet. This is the focal point of the beam. For sharp focus, the focal point should be exactly at the point where the beam reaches the screen.

A crt used in oscilloscopes and other test equipment. This tube uses electrostatic deflection and focusing.
Courtesy Waterman Products Co.

The focal point can be changed by adjusting the strength of the electric field in Figure 4. The field strength depends on the difference of potential between the first and second anodes; therefore, the focus can be adjusted by simply varying the voltage difference between the anodes. Usually, the voltage on the second anode is held constant and the voltage on the first anode, or **FOCUSING ANODE,** is varied to provide the desired focus.

The second anode is called the **ACCELERATING ANODE** because it speeds up, or accelerates, the electrons so that they strike the screen with enough force to cause light emission.

In most modern crt's, a uniform accelerating field exists from the electron gun to the screen. This field comes from an extension of the second anode in the form of an **AQUADAG** coating.

Aquadag is a conductive material, such as graphite, which is painted on the inside of the glass tube, as indicated in Figure 5. This coating is connected to the second anode by contacts called spiders. Besides producing a uniform accelerating field, the aquadag coating also serves as a collector for electrons which have struck the screen and thus served their purpose.

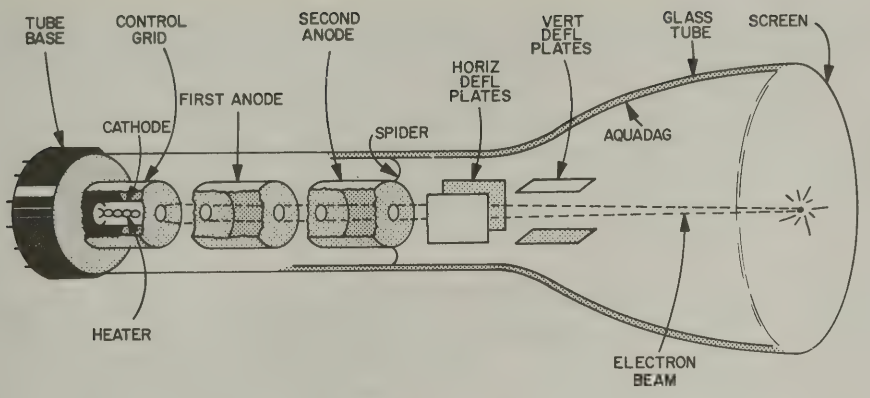


Figure 5

The Screen

The crt screen is struck by the electron beam to form an image. The screen is a coating of phosphor material on the inside of the glass tube face. The **PHOSPHOR** gives off light when it is struck by high speed electrons. This type of light emission is called **LUMINESCENCE.**

Luminescence is a general term used to describe the emission of light by the phosphor screen. There are two types of luminescence—fluorescence and phosphorescence. The light given off while the phosphor is actually being struck by the beam of electrons is called **FLUORESCENCE.** The term **PHOSPHORESCENCE** refers to the light given off by the phosphor immediately after the electron beam has been removed. Phosphorescence may therefore be described as an afterglow.

The type of phosphor that is used determines whether the light given off during fluorescence and phosphorescence will be the same color or will be different colors. Different types of phosphors produce different colors. CRT's are available with phosphors that will satisfy many different applications.

A list of phosphors appears in the Appendix at the end of this lesson. Some types are not shown because they are no longer in common use. Each phosphor type has its most important properties listed, along with its most common applications.

An important property of a crt is the **PERSISTENCE** of the screen. PERSISTENCE IS A MEASURE OF THE LENGTH OF TIME A PHOSPHOR GLOWS AFTER IT HAS BEEN STRUCK BY AN ELECTRON BEAM. Thus, it is an indication of the duration of phosphorescence in a crt. Persistence is described as being very short, short, medium short, medium, long or very long. A phosphor with very short persistence glows for less than a microsecond. The persistence of a short phosphor is from 1 microsecond to about 10 microseconds. Medium short persistence lasts from 10 microseconds to 1 millisecond. Medium persistence describes an afterglow that lasts from 1 millisecond to 100 milliseconds. Long persistence describes any afterglow that lasts between 100 milliseconds and 1 second. Very long persistence is a glow that lasts more than 1 second.

A short persistence crt is desirable for viewing fast changing images. Medium persistence screens are desirable in applications where the image does not change rapidly. If the same signal is repeated time after time and must be observed and studied, a long persistence screen is used.

For certain applications, two or more types of phosphors can be combined. For example, you may need a crt that has a very bright image for a long period of time. Since no single type of phosphor offers these characteristics, two different phosphors are coated on the same screen. A layer of phosphors with a bright light characteristic is coated over a layer of phosphors having long persistence. When the electron beam strikes the screen, the result is a bright image with long persistence. When more than one type of phosphor is used on a screen, the crt has a **CASCADE SCREEN.**

Most crt's are coded for easy identification. The code is a combination of letters and numbers. It describes the size of the screen, the crt's registration date and the type of phosphor used on the screen. For example, one type of crt is coded as 5AP1. The first number represents the screen diameter of a round face crt or the diagonal distance from corner to corner of a rectangular face crt. In this case, 5 represents a 5 inch diameter screen. The letter A tells us that this tube was the first type of 5 inch crt to be registered as a standard type in the electronic industry.

The last letter-number combination tells us the type of phosphor used on the crt screen. As shown in the table in the Appendix of this lesson, a P1 phosphor produces green light and has medium persistence. The main uses of the 5AP1 tube are in oscilloscopes and radar indicators.

The 3KP1 is an electrostatic crt with high deflection sensitivity. It provides a green image with medium persistence.
Courtesy Radio Corporation of America, Electron Tube Division

The following Practice Exercise questions cover the subjects which you have just studied. They are:

GENERAL DESCRIPTION OF THE CATHODE RAY TUBE

CONSTRUCTION AND OPERATION OF THE CATHODE RAY TUBE

THE ELECTRON GUN

THE SCREEN

1. What is the basic purpose of a cathode ray tube?
2. How is the position of the electron beam changed?
3. Name the three main sections of a crt.
4. Producing an electron beam is the function of the (a) deflection plates, (b) screen, (c) electron gun.
5. In what section of a crt is the electron beam bent from its normal path?
6. The electron beam traces an image on the crt ______________.
7. Name the five elements that make up the electron gun shown in Figure 2.
8. Explain the functions of the following electron gun parts: cathode, control grid and first anode.
9. Which element in the electron gun of Figure 2 speeds up the electrons as they move toward the screen?
10. The second anode of a crt is normally operated at a negative potential with respect to the cathode. True or False?
11. Electrostatic lines of force exist between electrodes having equal potentials. True or False?
12. Electrons tend to follow electrostatic lines of force. True or False?
13. In addition to helping to focus the electron beam, what other important function does the second anode serve?
14. What electron gun voltage is varied by the focus control?

15. **What is the name of the graphite coating on the inside of the glass envelope of a crt? What purpose does it serve?**

16. **What property of the screen phosphor produces a visible image on the crt screen?**

17. **When applied to crt screens, what is the meaning of the terms fluorescence and phosphorescence?**

18. **What characteristics would you expect from the screen of a 5UP1 crt? How would this screen compare to that of a 5BP1?**

The Deflection System

To produce a picture of an applied voltage, the electron beam must be deflected, or caused to move across the screen. Since almost all oscilloscopes use **ELECTROSTATIC DEFLECTION,** the electron beam is deflected by electrostatic fields between two sets of deflection plates. A voltage applied between each set of plates causes electrons passing between the plates on their way to the screen to be attracted by the positive plates and repelled by the negative plates, thereby deflecting the electron beam both vertically and horizontally.

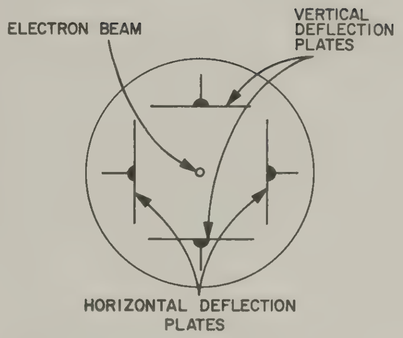


Figure 6

Figure 6 shows a front view of the two sets of deflection plates as seen from the screen end of the crt. The deflection plates are labeled according to the direction they force the electron beam to move. The horizontal deflection plates are mounted vertically on either side of the electron beam. The potentials applied to these plates cause the beam to move to the left or to the right. The vertical deflection plates are mounted horizontally above and below the beam, and the potentials applied to them deflect the beam up or down.

Changing voltages applied to the deflection plates change the movement of the electron beam across the screen. For example, when the left horizontal deflection plate is positive with respect to the right horizontal deflection plate, the beam is shifted to the left, which causes the image on the screen to move to the left. If the polarities on the plates are reversed, the beam moves to the right and causes the image to move to the right.

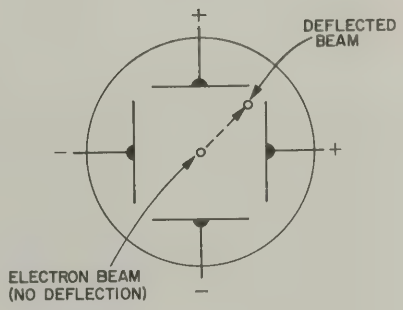


Figure 7

The voltages on the vertical deflection plates move the electron beam up or down. If the upper plate is positive with respect to the lower plate, the beam moves up. If the lower plate is positive with respect to the upper plate, the beam moves down.

When different potentials are applied to both sets of deflection plates at the same time, the electron beam moves horizontally and vertically at the same time. In Figure 7, voltages are applied so that the upper vertical deflection plate and the right horizontal deflection plate are positive by the same amount. The electron beam is attracted equally by these plates. The beam is deflected at an angle, to the right and upward. The result of these forces is a light spot image appearing in the upper right corner of the screen.

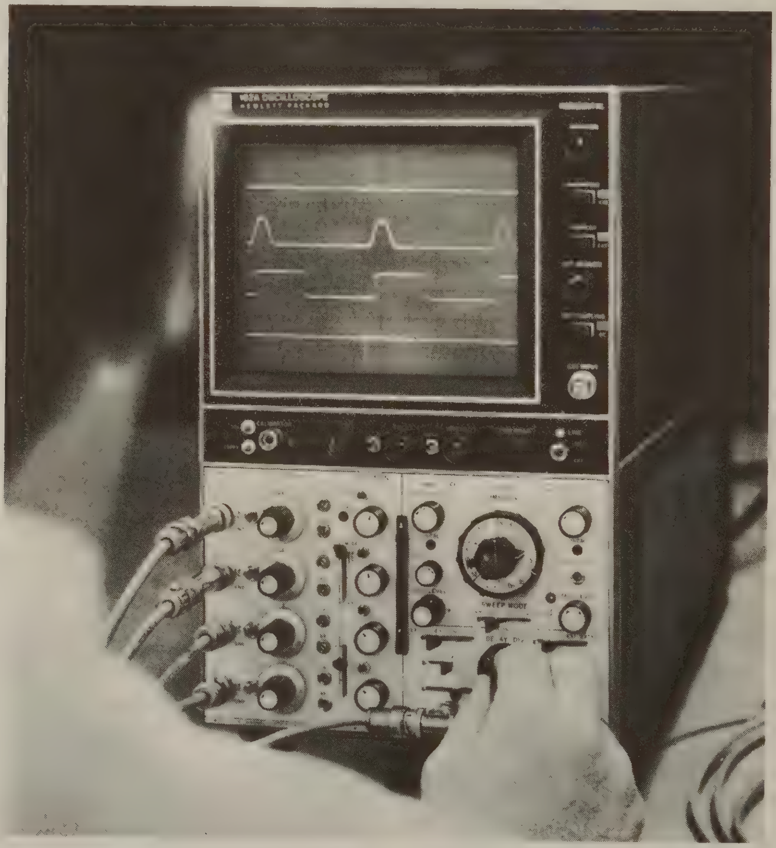
If repetitive changes of voltage are applied to the deflection plates, they cause the electron beam to move across the screen in some pattern. The pattern of light on the screen is often referred to as a **TRACE.** Because it is produced by the changes of voltage applied to the crt, the trace is actually a "picture" of the applied voltages.

Deflection Sensitivity and Deflection Factor

Two quantities that are given as both crt and oscilloscope specifications are DEFLECTION SENSITIVITY and DEFLECTION FACTOR. The magnitudes of these quantities are different for crt's than they are for scopes. For a crt, **DEFLECTION SENSITIVITY** indicates how far the beam will move for each volt applied between a set of deflection plates. **DEFLECTION FACTOR** indicates how much voltage must be applied between the deflection plates to move the beam a specified distance.

Most manufacturers also list a scope's deflection sensitivity. Deflection sensitivity expresses how far the beam moves for each volt of signal applied to the vertical input terminals.

The distance the image moves is expressed in terms of inches, centimeters or millimeters. For example, one manufacturer may describe an oscilloscope



Another high quality laboratory type oscilloscope. In addition to triggered sweep circuits and calibrated time base, it features 4-trace display capability and front panel plug-in units.

Courtesy Hewlett Packard

as having a vertical deflection sensitivity of .02 inch per volt dc. This means that under proper operating conditions, the image will move .02 inch up or down for each volt dc applied to the vertical input terminals.

Another means of rating deflection systems is by deflection factor. This term refers to the voltage needed at the vertical input terminals to deflect the beam a specified distance (1 inch, 1 centimeter, etc.). Deflection factor is the reciprocal of deflection sensitivity. For example, a tube that has a deflection sensitivity of .02 inch per volt dc would have a deflection factor of $^1/_{.02}$, or 50 volts dc per inch.

GENERAL DESCRIPTION OF THE OSCILLOSCOPE

Most cathode ray oscilloscopes in use today can be represented by the block diagram of Figure 8. Here we see the basic scope sections and their relationship to each other. In this diagram, the oscilloscope is divided into six sections: the Cathode Ray Tube, the High-Voltage Power Supply, the Low-Voltage Power Supply, the Vertical Amplifier, the Horizontal Amplifier and the Horizontal Sweep section. All of these sections have one end purpose—to display a pattern (trace) on the face of the cathode ray tube.

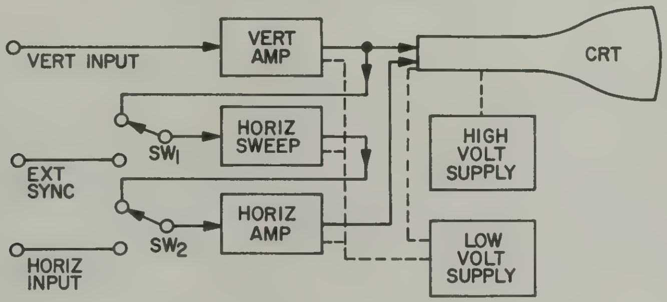


Figure 8

The high- and low-voltage power supplies provide the dc operating voltages for the crt and for other sections of the scope. In Figure 8, the power supply blocks are joined to the scope sections that they supply by dashed lines. When the crt and both power supplies are operating properly, a single spot of light is obtained near the center of the crt screen.

The signal applied to the horizontal amplifier section is supplied by the sweep section of the oscilloscope or by an external source. The horizontal amplifier section supplies an amplified signal to the horizontal deflection system of the crt. This signal causes the spot to move from side to side on the screen of the crt to produce the horizontal trace.

In Figure 8, switch SW_1 permits selecting either the vertical amplifier output or a signal from the EXT SYNC terminal as a synchronizing voltage for the horizontal sweep section. Switch SW_2 connects either the output of the sweep section or the signal at the HORIZ INPUT terminal to the horizontal amplifier section.

With all sections of the scope functioning properly (except the vertical amplifier), it is now possible to obtain a single horizontal line on the crt screen.

The actual test signal that we wish to observe is usually applied to the vertical amplifier section, whose main function is to amplify the test signal. After the test signal is amplified, it is applied to the vertical deflection system to cause the trace to move up or down on the screen of the crt. With simultaneous horizontal and vertical movement of the electron beam a complete waveform, or image, is formed on the crt screen.

To fully understand the operation of an oscilloscope, it is necessary to study the functions of the different scope sections in more detail.

POWER SUPPLIES

A modern oscilloscope must have a high-voltage power supply and also low-voltage power supplies which provide all of the required low-voltage sources for the amplifiers and deflection circuits. Each of these supplies contains rectifiers and filters to provide sufficiently ripple-free dc voltages for various sections of the scope. Zener diodes are employed in some power supplies for greater regulation, resulting in more precise scope measurements.

A typical oscilloscope power supply is shown in Figure 9. A single power transformer, T_1, is used to provide the necessary ac voltages. The high-voltage section is a voltage doubler type connected to provide a dc voltage that is negative with respect to ground. The low-voltage supplies utilize full-wave bridge rectifiers. The supply for $+V_{CC}$ and $-V_{CC}$ is voltage regulated by transistor Q_1. The two output zener diodes, ZD_4 and ZD_5, are connected in series and tied to ground to effectively provide two separate supplies, one a positive supply ($+V_{CC}$), the other a negative supply ($-V_{CC}$).

Optimum focusing in a crt is possible only when the difference of potential between the accelerating anode and the deflection plates is at a minimum, since any additional lines of force cause an already focused beam to defocus. Since the deflection plates are connected directly to the outputs of

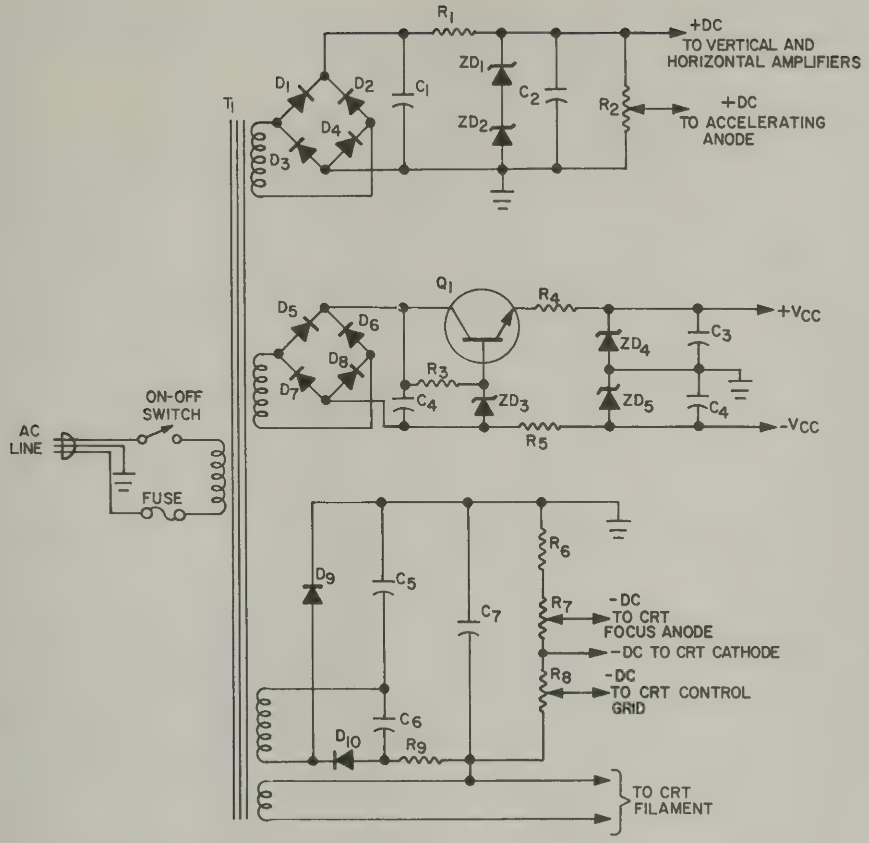


Figure 9

the vertical and horizontal amplifiers, the plates will generally receive a relatively low positive voltage with respect to circuit ground. Therefore, a relatively low positive voltage should be applied to the accelerating anode. This can be easily accomplished by using a high negative voltage for the focus anode, and a low positive voltage for the accelerating anode.

Figure 10 shows how the required negative and positive power supply voltages are applied to the crt electrodes. These voltages are obtained from voltage dividers connected to the power supply outputs shown in Figure 9.

As shown in Figure 10, the crt grid is connected to a more negative voltage point than the cathode is connected to. Varying the voltage on the grid (bias voltage) controls the number of electrons forming the beam that strikes the crt screen. The number of electrons striking the screen in a given amount of time determines the brightness of the trace on the screen. The potentiometer (R_8) that varies the bias voltage is commonly referred to as a **BRIGHTNESS CONTROL** or **INTENSITY CONTROL.** This control is usually found on the front panel of the scope.

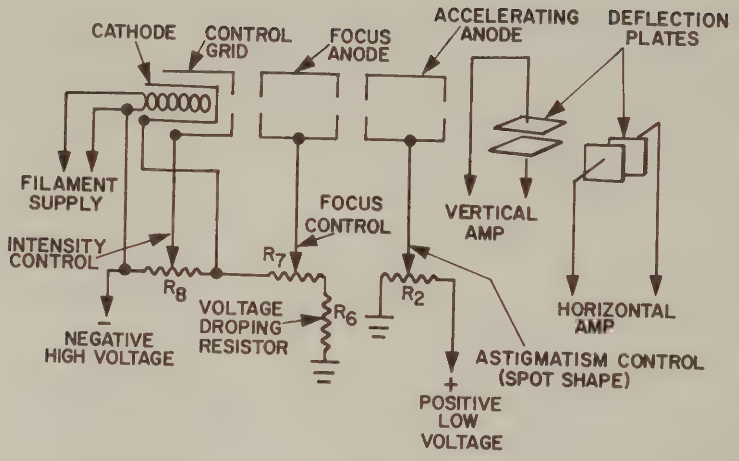


Figure 10

The focus anode, connected to a more positive point on the negative voltage divider, attracts the electrons which pass through the control grid. The shapes of the control grid and focus anode cause the electrons to travel along the tube axis and they are accelerated by the large potential difference between the focus anode and the accelerating anode. The strong electrostatic field between the focus anode and the accelerating anode, caused by the great difference of potential between them, provides electrostatic focusing of the beam. There is also a slight focusing action between the focus anode and the control grid, but most of the focusing takes place between the focus anode and the accelerating anode.

The electron beam is focused into a small spot on the crt screen by changing the difference of potential between the focus anode and the accelerating anode by adjusting potentiometer R_7 in the high-voltage negative power supply. In most scopes, this potentiometer is referred to as a **FOCUS CONTROL** and it is usually found on the scope's front panel.

When the beam is adjusted for sharp focus at the center of the crt screen, it will be slightly out of focus near the edges of the screen due to the deflection voltage on the plates. A control that allows small changes in the accelerating anode potential can be used to compensate for most of this misfocusing. The potentiometer that serves this purpose is usually called the **ASTIGMATISM CONTROL** or **SPOT SHAPE CONTROL**. The focus and astigmatism controls can be alternately adjusted to provide relatively sharp focus over most of the crt screen. The astigmatism control may be found on the front panel in some scopes; however, since it does not require frequent adjustment, some manufacturers mount it on the chassis inside the cabinet, or on the rear of the cabinet.

The following Practice Exercise questions cover the subjects which you have just studied. They are:

CONSTRUCTION AND OPERATION OF THE CATHODE RAY TUBE

THE DEFLECTION SYSTEM

DEFLECTION SENSITIVITY AND DEFLECTION FACTOR

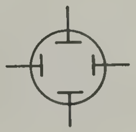
GENERAL DESCRIPTION OF THE OSCILLOSCOPE

POWER SUPPLIES

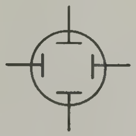
19. Why does a set of charged plates shift the position of an electron passing between them?

20. In Figure 6, which set of deflection plates causes an electron beam to move from right to left across the crt screen?

21. Label the horizontal and vertical deflection plates in the figure shown below.



22. In the following diagram, show where the electron beam would be deflected if the upper plate is more negative than the lower plate at the same time that the left plate is more negative than the right plate.



23. What does the term "deflection sensitivity" mean?

24. What is the deflection sensitivity of an oscilloscope if 0.5 volt causes the beam to move 2.5 inches vertically from its undeflected position?

25. Some oscilloscope catalogs include deflection factor in the specifications. What does the term "deflection factor" mean?

26. What is the deflection factor in inches of the oscilloscope of Practice Exercise 24?

27. Name the six sections that make up a general purpose oscilloscope.

28. Usually, an oscilloscope contains both high- and low-voltage power supplies. True or False?

29. What is the purpose of the horizontal deflection system of a scope?

30. In a general purpose oscilloscope, the voltage to be observed is usually applied to the (a) electron gun, (b) vertical amplifier system, (c) horizontal deflection system.

31. In most general purpose oscilloscopes, the brightness or intensity of the spot is varied by varying the bias on the crt. True or False?

32. A common method of focusing the pattern on the screen of a scope is to vary the voltage on the (a) control grid, (b) focus anode, (c) cathode of the crt.

33. To what part of a general purpose oscilloscope is the high-voltage power supply connected?

34. With respect to ground, the output of the high-voltage supply in Figure 9 is (a) positive, (b) negative.

AMPLIFIER SECTIONS

An oscilloscope uses an electron beam to trace pictures of the waveforms of voltages applied to its input terminals. It does this by applying signals to the crt deflection system to cause the beam to trace a pattern of light on the screen. The signals fed into the scope are usually too small in amplitude to deflect the electron beam directly. Therefore, the signals must be amplified before they are applied to the deflection plates.

Both the horizontal and vertical deflection systems contain amplifiers. These amplifiers increase the sensitivity of the oscilloscope by increasing or amplifying the signals applied to the deflection plates of the crt.

Vertical Deflection Amplifier

The electron beam is repetitively swept left to right across the crt screen, turned off during retrace periods, and turned on again for each subsequent sweep. During the time intervals that the beam is swept horizontally across the screen, it is also deflected vertically by the input signal waveform that is applied to the vertical amplifier section of the oscilloscope. The vertical amplifier must provide sufficiently high gain so that low-amplitude signals can be observed, or so that small portions of a test signal can be studied in detail. A good oscilloscope should be able to reproduce voltage waveforms with a minimum of distortion. To pass signals with minimum distortion, the vertical amplifier must have a sufficiently wide frequency response. If the amplifier does not have good frequency response, it does not amplify all signal frequencies (and their harmonics) by the same amount and the pattern on the screen may not be a true picture of the signal under test.

An oscilloscope should have a very high input impedance to obtain proper reproduction of an input signal. The high input impedance prevents the scope from loading the circuit being tested.

Figure 11 shows a simplified schematic of a typical scope vertical amplifier. The test signal is applied through capacitor C_1 to the gate of transistor Q_1. This transistor is a junction field effect transistor (JFET) connected in the common-drain amplifier (source follower) configuration. The common-drain JFET circuit provides the very high input impedance that is desirable in an oscilloscope.

Transistor Q_3 acts as a constant current source for Q_1. The constant current is produced because the base-to-emitter voltage of Q_3 is held constant by diodes D_1 and D_2. The voltage drop across a forward-biased silicon diode is

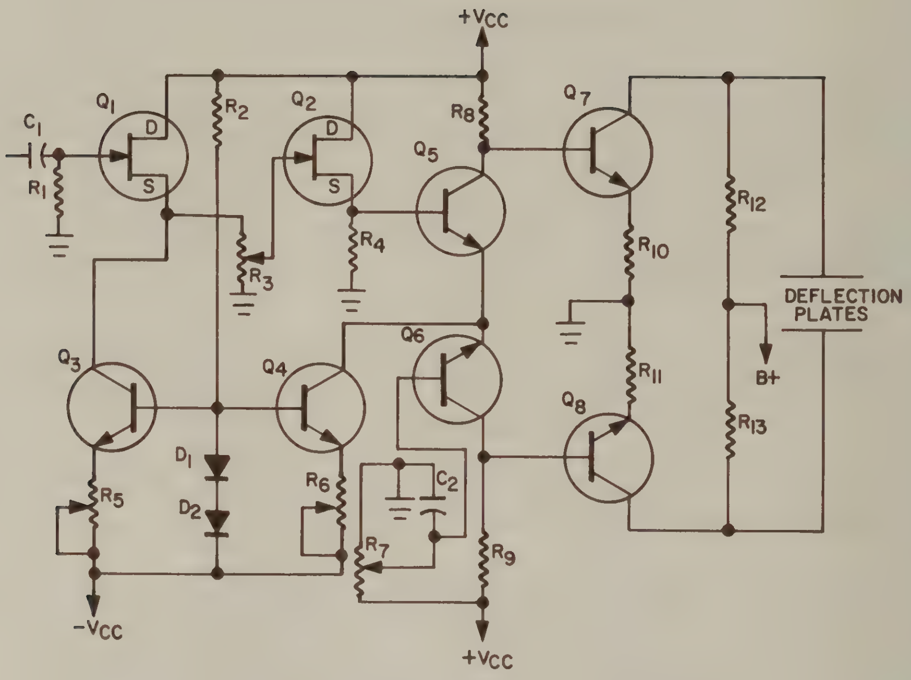


Figure 11

relatively constant (about .6 volt) over a wide range of current through the diode. Diodes D_1 and D_2 therefore maintain a constant 1.2 volts between the Q_3 base and $-V_{CC}$.

The amount of current through Q_3 is controlled by adjusting dc balance potentiometer R_5. Because the voltage across R_5 is held constant, changing its resistance changes the amount of constant current through the circuit. R_5 is adjusted so that the Q_1 source and the top of R_3 are at zero volts dc when there is no input signal to the vertical amplifier. This dc balance potentiometer is usually found on the chassis of oscilloscopes that employ this control.

With no drain resistor, the current through transistor Q_1 is also constant, and the test signal voltage at the Q_1 gate will cause voltage changes only at the Q_1 source. The Q_1 source voltage changes are applied across potentiometer R_3 to the Q_2 gate. R_3 varies the amplitude of the test signal in conjunction with a step attenuator at the vertical input of the scope. Potentiometer R_3 is often referred to as a **VERTICAL AMPLITUDE CONTROL** or **VERTICAL GAIN CONTROL.** This control is usually found on the front panel of most oscilloscopes.

Since the source voltage of Q_1 is applied to potentiometer R_3, the dc voltage at the gate of transistor Q_2 will remain at zero, regardless of the setting of R_3.

Setting R_5 for zero voltage at the Q_1 source results in a dc balance for the vertical amplifier. A portion of the test signal (selected by the vertical gain control) is applied to the gate of transistor Q_2. This transistor, like Q_1, is connected in the common-drain configuration and it is used to isolate the base current changes of transistor Q_5 from the test signal voltage changes across potentiometer R_3.

Transistors Q_5 and Q_6 are connected as a two-transistor phase inverter circuit. The circuit of transistor Q_4 is another constant current arrangement that uses diodes D_1 and D_2. The circuit of Q_4 is connected as the common-emitter resistance for phase inverter transistors Q_5 and Q_6 which basically function as a differential amplifier. Due to this constant current circuit, any change in the emitter current through Q_5 results in an equal and opposite emitter current change through Q_6. The test signal applied to the Q_5 base therefore appears amplified and inverted at its collector. The inverted version of the test signal at the Q_6 emitter also appears inverted and amplified at the Q_6 collector.

The two outputs of the phase inverter circuit are directly coupled to the push-pull output amplifiers (transistor Q_7 and Q_8). Except for the capacitor at the input of the vertical amplifier, all stages in the vertical section are direct coupled. This requires that circuit component values be selected so that the resultant potentials at the transistor elements will permit proper operation. In this instance, proper operation means that the transistors amplify in a linear manner at the correct operating points through proper biasing to achieve the desired potentials on the vertical deflection plates. The operating point of the phase inverter circuit, controlled by the constant current circuit of Q_4, will directly affect the operating point of the output amplifiers. The collectors of the output amplifiers are connected directly to the deflection plates. Therefore, the voltages on the deflection plates may be varied by adjusting the amount of the current through the constant current circuit. This is accomplished by adjusting the value of potentiometer R_6. This potentiometer is usually found on the chassis of the oscilloscope.

Since the emitters of transistors Q_5 and Q_6 are connected together, both transistors will function at the same operating point when their bases are at the same potential and their load resistors are equal. The dc voltage at the base of Q_5 is determined by Q_2 since the two transistors are direct coupled. However, the dc voltage at the base of Q_6 is controlled by potentiometer R_7.

Potentiometer R_6 is used to set the dc voltage on the vertical deflection plates to the correct operating voltage. Potentiometer R_7 sets a difference of potential on the deflection plates to change the vertical position of the trace. When the voltages on the deflection plates are equal, the trace will be in the center of the crt screen. When the voltages are not equal (determined by the setting of R_7), the trace is positioned above or below the center line. Since R_7

positions the trace, it is commonly called the **VERTICAL POSITIONING CONTROL.** This control is usually found on the front panel of most oscilloscopes.

AC coupling is used at the input to this circuit to eliminate the dc component of the test signal. However, in some measurements, the dc component is of prime importance. In such cases, the amplifier must be capable of amplifying dc signals as well as ac signals. To accomplish this, capacitor C_1 is simply shorted out so that the amplifier is completely dc coupled.

Horizontal Deflection Amplifier

In most scopes, the horizontal amplifier circuit is similar to the vertical amplifier circuit. Vertical deflection signals are fed through one amplifier, such as that shown in Figure 11, to the vertical deflection plates. Horizontal deflection signals are fed through the other amplifier, which is also a circuit like that of Figure 11, to the horizontal deflection plates.

When the circuit of Figure 11 is used as a horizontal deflection amplifier, the collectors of Q_7 and Q_8 connect directly to the horizontal deflection plates. Thus, horizontal sweep signals applied to the input cause the beam to sweep from left to right across the screen. R_7 again serves as a positioning control by varying the dc emitter voltage of Q_6. In a horizontal amplifier, this would be the **HORIZONTAL POSITIONING CONTROL.** R_3 serves as the **HORIZONTAL AMPLITUDE CONTROL, HORIZONTAL GAIN CONTROL** or **WIDTH CONTROL.**

The width control and the horizontal positioning control are usually found on the front panel of the oscilloscope. The other two controls of this circuit (potentiometers R_5 and R_6) are usually found on the chassis in scopes where they are used. Potentiometer R_5 is used to set the dc balance of the horizontal amplifier and R_6 is used to set the operating voltages on the deflection plates.

Usually, the horizontal amplifier section is not required to have as much gain or as wide a frequency response as the vertical amplifier section. However, the horizontal gain should be great enough to sweep the beam across the entire screen, with enough additional gain so that the pattern can be expanded to study small sections of a waveform.

The signal normally applied to the horizontal amplifier section is generated in the sweep section of the oscilloscope (discussed later in this lesson). This

A general purpose service oscilloscope. Its sensitivity and frequency response in both the vertical and horizontal sections are more than adequate for the average service technician.

Courtesy Dynascan Corp.

signal is usually a ramp voltage (sawtooth) that is amplified by the horizontal amplifier and applied to the horizontal deflection plates. This causes the voltages applied to the horizontal deflection plates to change in a linear manner during the sweep, while maintaining a constant difference of potential between the plates. The ramp voltage thus causes the electron beam to sweep across the face of the crt to produce a visible trace. The sweep rate of the electron beam is determined by the sawtooth frequency generated in the sweep section.

A second signal that is sometimes applied to the horizontal amplifier is an external signal normally related to the test signal that is applied to the vertical amplifier section. When connected in this manner, the relationship between the applied signals can be observed on the crt screen.

The internal horizontal sweep frequency repetition rate of a general purpose scope is usually less than 700 kHz. The response of a horizontal amplifier is usually wide enough to pass this frequency with very little distortion.

Attenuator Networks

If the input signals are too large, the transistors in the deflection amplifiers will be overdriven. This causes distortion in the output signal waveform, and the pattern on the screen is not a true picture of the input signal. This distortion is prevented by limiting the signal amplitude applied to the transistors.

When the signal amplitude is reduced in any manner, the action is called **ATTENUATION.** Any component or network of components used for this purpose is called an **ATTENUATOR.** A simple form of attenuator is a potentiometer.

The input signals to the vertical sweep amplifier will normally cover a range from a few millivolts to over 100 volts. A suitable attenuator must be used at the scope input to reduce large input signals to manageable levels. However, the attenuator must not alter characteristics such as input signal waveshape. If a potentiometer were to be used as the input attenuator, it would sometimes alter signal characteristics.

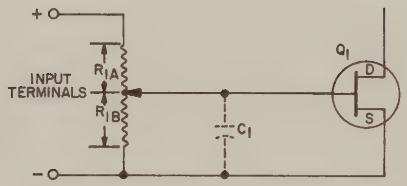


Figure 12

Figure 12 shows how a potentiometer would be used to vary the input signal. Dashed-line capacitor C_1, which represents the distributed capacitance between the movable arm and lower terminal of potentiometer R_1, would also be present. C_1 includes the capacitance of the potentiometer leads, the wiring capacitance in the Q_1 gate circuit and the gate-source capacitance of the JFET. Capacitor C_1 is in series with the upper portion of the potentiometer (R_{1A}), and in parallel with the lower portion (R_{1B}).

The entire resistance element of R_1 is across the input terminals, regardless of the setting of its movable contact, and the scope presents a fairly constant load to the signal source under test. If the potentiometer resistance is high, the scope does not load down the test circuit to any great extent. However, the distributed capacitance of the transistor's gate circuit forms a low-pass network with the upper portion of the potentiometer. This causes greater attenuation of high frequencies than of low frequencies, which limits the frequency response of the oscilloscope.

Because C_1 cannot be eliminated, its presence must be compensated for. This could be done by connecting a capacitor across section R_{1A} of the potentiometer. This capacitor and R_{1B} form a high-pass network which compensates for the effect of the C_1R_{1A} low-pass network. This is not practical because the capacitor value must be changed every time the setting of the potentiometer is varied. However, it can be done very easily by using a switch-type attenuator instead of the potentiometer.

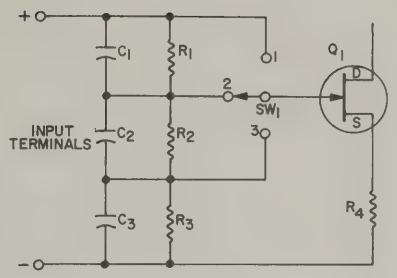


Figure 13

In Figure 13, the potentiometer and the capacitors have been replaced by a switching arrangement of fixed value resistors and capacitors. The values of the capacitors are chosen to compensate for the effect of distributed capacitance on different values of attenuation resistance over a wide range of frequencies.

A switch-type attenuator is often referred to as a **STEP ATTENUATOR.** For continuously variable operation, a potentiometer is also used at a point in the circuit where it will not adversely affect frequency response.

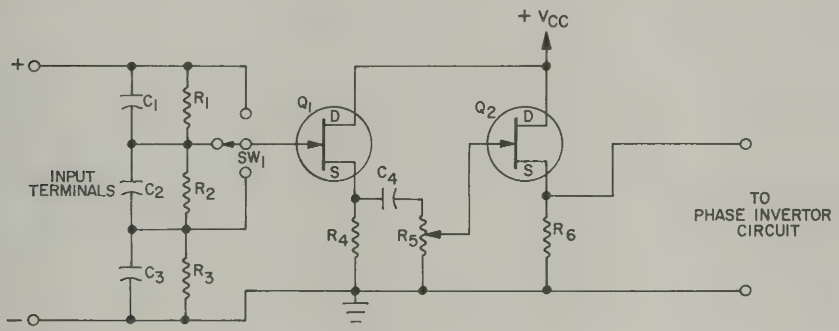


Figure 14

Figure 14 shows an input circuit that offers high input impedance, good frequency response and continuously variable control over the input signal. This network is composed of a step attenuator, a source follower stage, a continuously variable attenuator and an isolation stage (also a source follower). The continuously variable attenuator, R_5, has been placed in a low impedance circuit where there is less effect due to undesirable capacitance. Many oscilloscopes use similar systems in their vertical input circuit.

The step attenuator is normally found on the front panel of the oscilloscope. The front panel is often marked to indicate the attenuation obtained with each switch position. Some scopes are calibrated to indicate the deflection of the trace for each vertical division marked on the crt screen when the continuously variable attenuator (vertical gain control) is set at minimum gain.

The input circuit shown in Figure 14 is an ac type. This circuit is converted to a dc type by replacing resistor R_4 with a constant current source, and eliminating capacitor C_4.

The high impedance of the input transistor, the frequency compensated attenuators and the wide frequency response of the vertical amplifier allow undistorted signals to appear at the vertical deflection plates. However, an additional circuit, referred to as a sweep generator, is required to move the trace horizontally at a uniform rate so that an accurate picture of the input signal is obtained.

HORIZONTAL SWEEP CIRCUITS

Most oscilloscopes contain an internal circuit for developing the repetitive signal waveform that is applied to the horizontal deflection plates. This signal voltage, used to repetitively sweep the electron beam horizontally across the crt screen, is produced by the **HORIZONTAL SWEEP CIRCUIT.** The beginning of each sweep voltage waveform is applied to the horizontal amplifier section at the same time that the beginning of a cycle of the test signal is applied to the vertical amplifier section.

An oscilloscope is a graphical display device that sweeps the electron beam horizontally across the screen at a linear rate. The test signal, applied to the vertical input, is then represented on the crt screen as a line or lines on a graph. That is, the changes in amplitude of the test signal are "plotted" with respect to time. In effect, the scope uses a beam of electrons to draw a waveform on the screen just as you use a pencil to draw a waveform on a piece of paper.

So that equal amounts of horizontal deflection represent equal intervals of time, a LINEAR horizontal sweep is required. The linear sweep voltage used in an oscilloscope changes uniformly from its minimum to maximum values, then drops very rapidly to minimum and repeats the cycle. This voltage, applied to the horizontal deflection plates, causes the electron beam to move horizontally at a constant speed, return rapidly to the starting point and then begin another linear sweep.

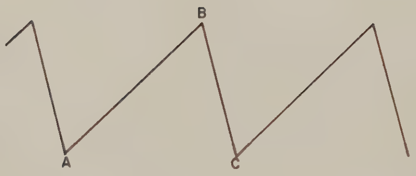


Figure 15

A common type of signal used to produce a linear sweep is a **SAWTOOTH** wave, as shown in Figure 15. The linear rise of the waveform from minimum to maximum occurs from point A to point B. The rapid decrease of the waveform from maximum to minimum occurs from point B to point C. A second sawtooth cycle then begins at point C, increases to maximum and then drops rapidly to minimum. The slower rising portion of the sawtooth wave produces the horizontal linear deflection of the beam called the trace. The rapid decrease of the sawtooth wave from maximum to minimum produces the return motion called the retrace.

One of the most common methods of developing a sawtooth voltage is to charge a capacitor through a high resistance; then discharge it through a low resistance. The capacitor charges slowly through the high resistance, as represented by the slowly rising voltage between points A and B on the sawtooth waveform shown in Figure 15. Then, the capacitor is discharged quickly through a low resistance. This is represented by the rapid fall in voltage between points B and C in the Figure 15 waveform.

Another method for developing a sawtooth voltage is to rapidly charge a capacitor through a low resistance; then discharge the capacitor through a high resistance. However, with either method, the output sawtooth signal will resemble the waveform shown in Figure 15. RC charge and discharge rates are not linear, as they follow exponential curves. However, if a very small portion of a long RC time is used for the trace, it will appear to be relatively linear. This is what is done in most expensive sweep generator circuits.

A simplified schematic of a sawtooth generator is shown in Figure 16. This circuit is basically a free-running multivibrator that rapidly charges one of the sawtooth-forming capacitors (C_1, C_2 or C_3) through the low resistance of R_5 and transistor Q_2 during the intervals when Q_2 conducts. When Q_2 cuts off, the capacitor slowly discharges through potentiometer R_4.

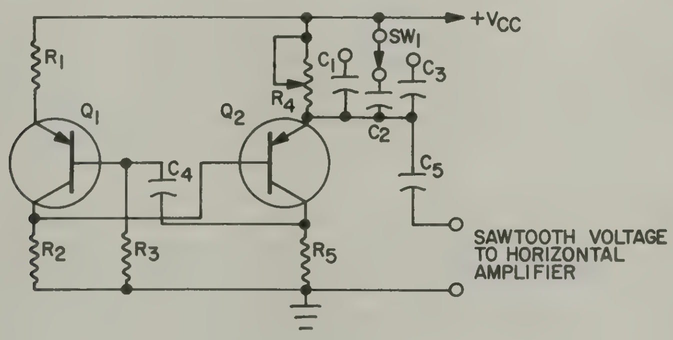


Figure 16

When power is applied to the circuit, the instantaneous voltage across capacitor C_2 (the sawtooth-forming capacitor that has been selected with switch SW_1) is zero. Therefore, the emitter voltage of transistor Q_2 is equal to the supply voltage ($+V_{CC}$), which causes Q_2 to conduct since it is forward biased by the less positive potential on the base.

When Q_2 conducts, the voltage at its collector rises. This applies a positive voltage through capacitor C_4 to the base of Q_1 to serve as a reverse bias that keeps Q_1 cut off.

This condition exists for a very brief time period during which capacitor C_2 charges through the low resistance of forward-biased transistor Q_2 and collector resistor R_5, which also must have a low resistance value. However, the Q_2 emitter voltage decreases rapidly as C_2 charges, decreasing the forward bias on Q_2. Q_2's collector voltage drops as the decreasing forward bias causes Q_2 to quickly come out of saturation. The rapidly decreasing Q_2 collector voltage, applied to the base of transistor Q_1, continues to drop until Q_1 becomes forward biased and starts to conduct.

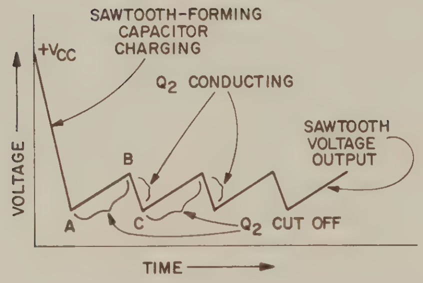


Figure 17

When transistor Q_1 starts conducting, its collector voltage rises. Since the Q_1 collector is direct coupled to the Q_2 base, this increasing voltage further reduces the Q_2 forward bias. The decreasing forward bias insures that Q_2 cuts off. This action is regenerative; therefore, Q_2 goes from saturation to cutoff in an extremely short time. The point at which Q_2 cuts off is indicated by point A in Figure 17.

When transistor Q_2 cuts off, voltage is no longer developed across resistor R_5 to forward bias Q_1. The Q_1 base voltage is now determined solely by biasing resistors R_1 and R_3. The resistance values of R_1 and R_3 are selected to hold Q_1 in conduction at this time. Transistor Q_2 remains cut off and Q_1 continues to conduct for the relatively long time period between points A and B of Figure 17. This is the linear trace interval.

With transistor Q_1 conducting, its positive collector voltage, which is fed to the Q_2 base, holds Q_2 in cutoff. The Q_2 emitter voltage increases relatively slowly as capacitor C_2 discharges through the high resistance of potentiometer R_4. Q_2 remains cut off until its emitter voltage increases enough for it to become forward biased.

The instant that transistor Q_2 starts to conduct, the regenerative action of the circuit rapidly switches Q_2 from cutoff to saturation. When Q_2 conducts, the positive voltage developed across resistor R_5 reverse biases transistor Q_1 to cutoff. When Q_1 cuts off, the voltage across resistor R_2 drops to zero, which increases the forward bias on Q_2. Therefore, Q_2 goes from cutoff to saturation in an extremely short period of time. The point at which Q_2 saturates is indicated by point B in Figure 17.

The saturation current through transistor Q_2 quickly charges capacitor C_2 again. The charge time is represented as the period between points B and C in Figure 17. This is the retrace interval. A second cycle of operation starts at point C when transistor Q_2 has again gone into cutoff.

The multivibrator circuit of Figure 16 will continue to oscillate as long as power is applied to the circuit. The varying voltage at the emitter of transistor Q_2 is in the form of a sawtooth. The sawtooth voltage is applied to the horizontal amplifier through capacitor C_5.

The resistance of potentiometer R_4 and the capacitance of the sawtooth-forming capacitor (C_1, C_2 or C_3), selected by switch SW_1, determine the rate, or frequency, at which the voltage across transistor Q_2 rises from minimum to maximum. Therefore, SW_1 serves as the **COARSE FREQUENCY CONTROL,** which changes the horizontal sweep frequency in large steps. R_4 is the **FINE FREQUENCY CONTROL,** or **FREQUENCY VERNIER CONTROL,** which permits continuous variation of frequency in the range selected by SW_1. Both of these controls are normally found on the front panel of the oscilloscope.

The free-running multivibrator may be used to produce the horizontal trace, but to make the circuit more useful in the oscilloscope, the sweep is triggered so that it will be synchronized to the test signal.

SYNCHRONIZATION

To obtain a stationary pattern on the oscilloscope screen, there must be some exact relationship between the frequency of the test signal and the horizontal sweep frequency. When the frequency of the test signal and the horizontal sweep voltage frequency are exactly equal, one complete cycle of the test signal appears on the screen. If the frequency of the test signal is exactly twice the horizontal sweep frequency, then two complete cycles of the test signal appear on the screen, and so on.

If there were no way to lock the horizontal sweep generator frequency to the test signal frequency, the scope's fine frequency control would have to be constantly adjusted to hold the crt pattern stationary. To avoid this problem, oscilloscopes include a means of synchronizing the sweep generator to the test signal. One method of accomplishing this is to trigger the multivibrator horizontal sweep circuit with pulses that are obtained from the test signal. The pattern will then remain stationary on the crt screen.

A simplified schematic of a typical sync circuit used to synchronize the sawtooth generator to the test signal is shown in Figure 18. The **SYNCHRONIZING SIGNAL,** commonly called the **SYNC SIGNAL,** is selected by switch SW_1 and is ac coupled to the sync circuit. The sync circuit controls, amplifies and shapes the sync signal into pulses that are used to trigger the sawtooth generator.

The sync signal may be obtained from the internal vertical amplifier or from the external circuit under test. The external signal is applied through

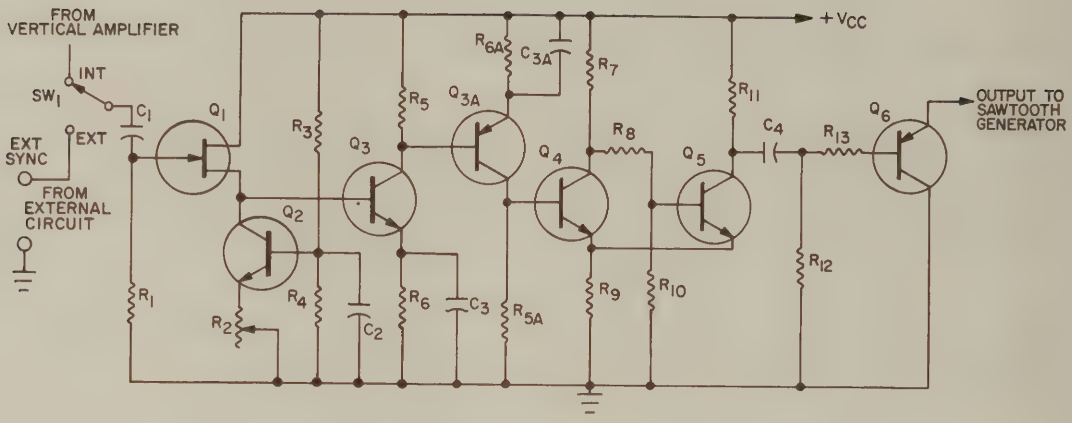


Figure 18

appropriate terminals which are usually located on the front panel of the oscilloscope. These terminals are often identified as the external sync (EXT SYNC) input terminals or external trigger (EXT TRIG) terminals.

Switch SW_1 is commonly called the **SYNC SELECTOR SWITCH,** or simply, the **SYNC SWITCH.** This switch is normally found on the front panel of the oscilloscope. The switch has two positions, marked INT (internal) and EXT (external), to permit the scope operator to select the sync signal he wishes to use.

The sync signal is applied to the gate of transistor Q_1. The output at the Q_1 drain is amplitude controlled by the constant current circuit of transistor Q_2. The current through Q_2 is relatively constant because of the fixed voltage on its base. The amount of constant current obtained is determined by the setting of potentiometer R_2, the Q_2 emitter resistor. Since the current through Q_1 is the combined currents of transistor Q_2 and the base current of transistor Q_3, any variation in current through Q_1 causes equal changes in the Q_3 base current. When a low-amplitude external signal is applied to the gate of Q_1, R_2 may be set to increase the gain of Q_1, and when a larger signal is applied to the input, R_2 may be set so that Q_1 has less gain. Therefore, potentiometer R_2 controls the amplitude of the sync signal applied to the base of Q_3.

The pattern on the crt screen is held stationary when potentiometer R_2 is set for a proper amplitude of sync signal at the base of current amplifier Q_3. Potentiometer R_2 is commonly referred to as the **SWEEP TRIGGER LEVEL CONTROL or SYNC AMPLITUDE CONTROL.** This control is usually found on the front panel of the oscilloscope. The sync signal is amplified by transistor Q_3 and is direct coupled through phase inverter Q_{3A} to the waveshaping circuit of Q_4 and Q_5.

The following Practice Exercise questions cover the subjects which you have just studied. They are:

AMPLIFIER SECTIONS

- VERTICAL DEFLECTION AMPLIFIER
- HORIZONTAL DEFLECTION AMPLIFIER
- ATTENUATOR NETWORKS

HORIZONTAL SWEEP CIRCUITS

35. To produce a waveform of adequate size when small signal voltages are being viewed, the vertical amplifier of an oscilloscope should provide high gain. True or False?

36. Why is a wide frequency response necessary for the vertical amplifier of an oscilloscope?

37. It is desirable for the vertical amplifier of a scope to have high input impedance and low shunt capacitance. True or False?

38. In the circuit of Figure 11, with respect to the signal voltage at the Q_5 collector, the signal voltage at the Q_6 collector is (a) in phase, (b) 180° out-of-phase.

39. What function does R_7 serve in the circuit of Figure 11?

40. If the circuit of Figure 11 is used as a horizontal deflection amplifier, what is the function of R_3?

41. In a general purpose oscilloscope, the gain of the horizontal amplifier is normally (a) greater than the gain of the vertical amplifier, (b) less than the gain of the vertical amplifier.

42. Why are capacitors usually connected across the resistors in an attenuator such as that of Figure 13?

43. The purpose of Q_1 in Figure 14 is to provide a large voltage gain. True or False?

44. A linear sweep is required in an oscilloscope so that equal amounts of horizontal deflection represent equal periods of time. True or False?

45. The type of waveform that is commonly used to produce a linear sweep in an oscilloscope is a (a) sinewave, (b) sawtooth, (c) straight line.

46. In the sawtooth generator of Figure 16, the slow, linear rise of the sawtooth occurs when Q_2 is (a) conducting, (b) cut off.

47. At a given setting of SW_1 in Figure 16, what would happen to the sawtooth frequency if R_4 were set to a higher resistance?

48. To produce a sawtooth waveform in the circuit of Figure 16, Q_2 must be cut off for a longer period of time than when it is conductive. True or False?

The waveshaping circuit is a bistable multivibrator constructed with a single emitter resistor (R_9) for regenerative feedback. This type of circuit is also known as a Schmitt trigger. With no input signal, transistor Q_5 conducts and transistor Q_4 is cut off. The Q_5 base voltage is set by the divider network of resistors R_7, R_8 and R_{10}. With Q_5 conducting, its emitter voltage keeps the Q_4 emitter positive with respect to the Q_4 base. This keeps Q_4 reverse biased. The Q_4 base voltage is set by the Q_{3A} voltage collector. When a sync signal causes transistor Q_{3A} to conduct more, its collector voltage increases, which increases the Q_4 base voltage. When the Q_4 base voltage increases to a voltage level which we will call E_{ON}, Q_4 starts conducting. The instant that Q_4 starts to conduct, its collector voltage decreases, which causes a decrease in the voltage at the Q_5 base. The decreasing Q_5 base voltage reduces the forward bias on Q_5, which reduces the current through Q_5.

This would also reduce the current through R_9, except that Q_4 is now conducting. Instead, the current through R_9 increases, increasing the R_9 voltage drop, which causes the Q_5 emitter voltage to rise, further reducing the forward bias on Q_5. The increase in current through Q_4 further decreases its collector voltage, which causes a still greater decrease in voltage at the base of Q_5. The continuing reduction of forward bias on Q_5 drives Q_5 into cutoff. This action of transistors Q_4 and Q_5 is regenerative, and once Q_4 starts to conduct, it changes very rapidly from cutoff to full conduction. At the same time, Q_5 changes from full conduction to cutoff. The circuit remains in this condition until the signal voltage at the base of transistor Q_4 drops to a level, E_{OFF}, that causes the current through Q_4 to start decreasing.

When the Q_4 base voltage drops to E_{OFF}, a regenerative action starts that rapidly changes Q_4 from full conduction to cutoff. As E_{OFF} is reached, Q_4 current decreases, increasing the Q_4 collector voltage and also the voltage at the base of Q_5. This increasing forward bias on Q_5 increases the voltage drop across emitter resistor R_9, which causes the decreasing forward bias on Q_4 to decrease even further, until Q_4 cuts off. At the same time, transistor Q_5 changes from cutoff to full conduction.

The shape of the output waveform produced by transistors Q_4 and Q_5 of Figure 18 does not depend on the shape of the input waveform. The output waveform only reflects the instant that the sync voltage signal at the base of Q_4 increases to E_{ON}, and the instant that the Q_4 base voltage signal drops to E_{OFF}. This type of waveshaping circuit always produces a rectangular output waveform.

The most important thing about the output of the waveshaping circuit is not the shape of the output signal, but the times at which the output waveform changes states. The output state changes have a precise relationship to the input signal voltage levels that trigger the state changes.

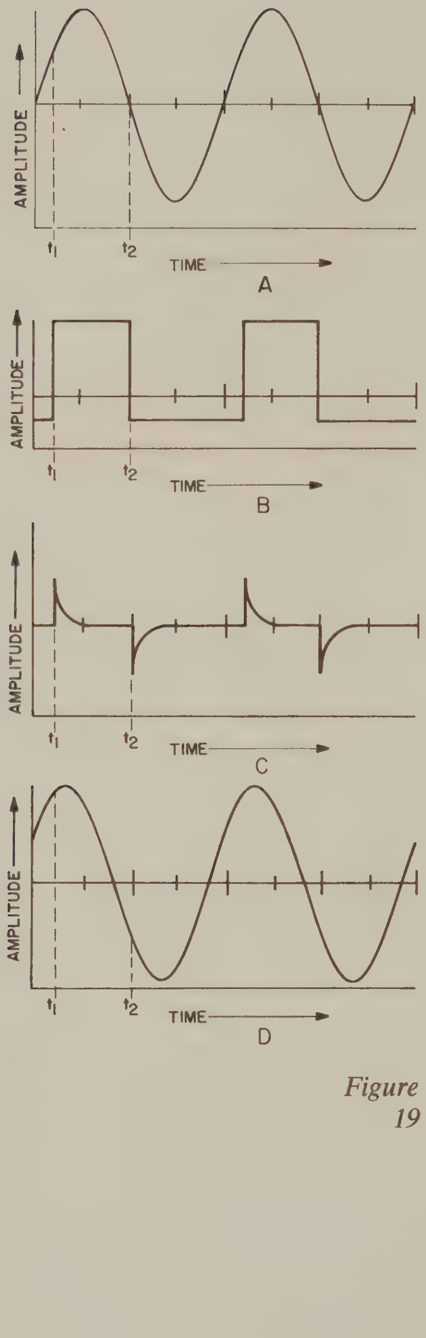


Figure 19

The shape of the rectangular output waveform at the Q_5 collector is altered by the short time constant high-pass network of capacitor C_4 and resistor R_{12} into positive and negative pulses. These pulses are amplified by transistor Q_6 and direct coupled to the sawtooth generator circuit. The positive pulse triggers the sawtooth generator to start a cycle of horizontal drive, synchronizing the trace with the test signal on the crt screen.

The waveforms in the sync circuit must be studied to understand the relationship of the sawtooth generator voltage to the test signal voltage. In Figure 18, ac signal at the gate of transistor Q_1 is in phase with the test signal. This sync input signal is shown in Figure 19A. The waveform has a positive slope when rising and a negative slope when falling.

Because Q_1 is a source follower, the Q_3 base signal polarity is the same as the sync input signal. The inverted output at the Q_3 collector drives Q_{3A}, whose collector waveform is an amplified version of the input signal, and has the same polarity as the input signal, as shown in Figure 19A.

We have noted that transistor Q_4 starts conducting when its base voltage reaches E_{ON}. In our example, E_{ON} has a value that is approximately 70% of the peak sinewave voltage. Therefore, Q_4 starts conducting and Q_5 stops conducting when the waveform shown in Figure 19A reaches 70% of its peak positive value. This is time t_1 in Figure 19A. This point in time is also shown in Figure 19B, which is the waveform obtained at the Q_5 collector. As transistor Q_5 cuts off, its collector voltage goes to maximum.

E_{OFF} (t_2) is lower than E_{ON}, about at the midpoint of the input signal waveform. When the waveform at the Q_{3A} collector drops to about zero volts, transistor Q_4 stops conducting and Q_5 starts conducting again. The Q_5 collector voltage then drops back to a low level, as shown at t_2 in Figure 19B. The RC circuit of resistor R_{12} and capacitor C_4 converts the rectangular waveform into pulses, shown in Figure 19C, that are applied to the sawtooth generator through transistor Q_6, where positive pulses trigger each cycle of the sawtooth waveform.

The positive pulse triggers the sawtooth generator when the test signal is going positive, resulting in a crt screen trace as shown in Figure 19D. Because the signal is on the positive slope as it starts, the pattern is triggered on the positive slope.

Since no other provisions are made in the circuit of Figure 18, it always triggers the pattern on the positive slope. The point on the slope at which the trace is triggered depends on when transistor Q_4 is turned on. Q_4 starts conducting when its base voltage reaches E_{ON}, and this voltage level can be varied by changing the amplitude of the sync signal. When the sync amplitude is increased, E_{ON} is reached sooner, so that Q_4 is triggered sooner. When the sync amplitude is decreased, Q_4 is triggered later; therefore, the pattern on the crt screen can be triggered at almost any point on the positive slope of the sync signal input.

It is common practice to illustrate waveforms starting on their positive slopes. For ease of comparison, the waveform on an oscilloscope should start on the same slope. The slope the pattern is triggered on is easily changed by adding an extra stage of amplification in the sync circuit. Frequently, both slopes are important, and many oscilloscopes contain slope triggering circuits to permit the pattern to be triggered on either slope.

SLOPE TRIGGER CIRCUIT

Triggering the sawtooth generator so that the test signal pattern on the crt screen starts on the desired slope is important, especially when observing only one or two cycles of a waveform. Because the two outputs of a differential amplifier are 180° out-of-phase, this type of circuit is often used at the input of a sync signal amplifier to allow switch selection of a sync signal of the desired slope. This circuit, shown in Figure 20, is commonly referred to as the **SLOPE TRIGGER CIRCUIT.**

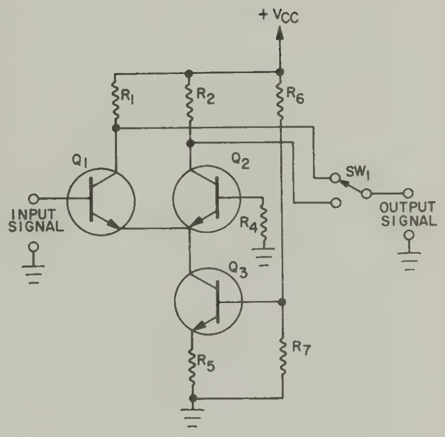


Figure 20

Switch SW_1 is commonly referred to as the **SLOPE TRIGGER SELECTOR** switch, or simply the **SLOPE SWITCH.** This switch is usually found on the front panel of the oscilloscope. The front panel is normally marked + (positive) and − (negative) to indicate the two switch positions.

COMPLETE OSCILLOSCOPE SCHEMATIC

We have studied some typical circuits which make up the main sections of an oscilloscope. Now, let's look at a complete oscilloscope schematic diagram and see how the various sections work together.

Figure 21 is a schematic diagram of a typical oscilloscope. In this transistorized scope the components are assembled on printed circuit boards in functional groups. Each printed circuit board is represented on the schematic by heavy dashed-line blocks that contain the components that are on the DC boards.

The power supply circuit board contains all of the dc power supplies, including the high-voltage supply. The horizontal circuit board contains the

A scope designed for either laboratory or service use. It incorporates many of the good qualities of the more expensive laboratory scopes but without the ultra wide band frequency response and dual-trace features.
Courtesy Dynascan Corp.

complete horizontal amplifier. The sweep circuit board contains the sync circuit and the sawtooth generator. The vertical circuit board contains the vertical amplifier, except for an input attenuator that is connected to the front panel. The crt is mounted on the chassis of the oscilloscope.

The test signal goes to the vertical input terminals, J_1 and J_2. This input is coupled to the attenuator network through the **VERTICAL AC-DC SWITCH** (SW_1). Switch SW_1, normally found on the oscilloscope front panel, allows the operator to view a total test signal (DC position) or eliminate the dc component in the test signal (AC position).

The step attenuator switch (SW_2) couples the test signal to the Vertical Circuit Board. Three of the positions of switch SW_2 allow the input signal to be attenuated by factors of 100, 10 or 1. The first position of SW_2 grounds the input of the vertical amplifier to allow accurate calibration of the amplifier's dc balance and the deflection plate voltages. This vertical amplifier is very similar to the vertical amplifier of Figure 11, except for some circuit refinements. Resistor R_1 protects transistor Q_1 if too high a potential is applied to the vertical amplifier input. Capacitor C_1 provides a path around R_1 to improve high-frequency response. Diode-connected transistors D_1 and

D_2 provide zener action that limits the input signal to approximately ±9 volts, which further protects Q_1 from input high-voltage damage.

Another refinement affords greater operator control. The Vertical Position control, potentiometer R_{10}, is made up of three pots instead of one. The coarse position control consists of two potentiometers that are connected so that as the resistance of one increases, the resistance of the other decreases, to maintain a constant resistance in the circuit. The voltage drop across the 100 ohm fine position control therefore remains constant, but the voltage applied to it changes from +9 volts to zero volts, depending on the setting of the coarse control. This arrangement permits more accurate setting of the vertical position of the trace. The coarse control is normally found on the chassis, and the fine control is a front panel control.

Degenerative feedback is commonly used in the amplifiers of an oscilloscope to assure good stability and better frequency response. The vertical amplifier of Figure 21 has one more gain stage than the circuit of Figure 11 to compensate for loss of amplification due to the use of degenerative feedback caused by the emitter resistors.

Judicious application of positive feedback can also increase frequency response. Capacitors C_3, C_4 and C_6, connected between the emitters of the push-pull amplifiers, provide regenerative feedback to boost the high-frequency gain. C_6 is a variable capacitor that allows adjustment for the broadest frequency response, so that the circuit amplifies a square wave accurately. This control is normally found on the chassis.

The circuits on the Sweep Circuit Board that are similar to the circuits of Figures 16 and 18 function in essentially the same manner. Resistor R_{101}, transistors D_{102} and D_{103}, and capacitor C_{101} are added to protect transistor Q_{101}. This operation is identical to that of the input protection components already described.

The circuit of transistor Q_{108} is used to cut off the crt electron beam during retrace. The positive pulse at the Q_{107} emitter that triggers the start of the sweep generator is amplified and inverted by Q_{108}, and applied to the control grid of the crt through capacitor C_{109}, causing blanking during the retrace.

The horizontal sweep sawtooth wave is generated by the circuit of transistors Q_{109} and Q_{110}. Another constant current circuit, that of transistor Q_{111}, is added to increase linearity of the sawtooth waveform. The sawtooth capacitors (C_{114}, C_{115}, C_{116}, C_{117} and C_{118}) are discharged at a constant rate, through Q_{111}, to insure a linear trace. In this scope, additional sawtooth generator capacitors are added in series for higher frequency steps of the coarse frequency control, instead of using different capacitors for each sweep rate change.

The circuit of the Horizontal Circuit Board is very similar to that of Figure 11. The Horizontal Circuit Board also has input protection, and the stability of the amplifier is increased by degenerative feedback. The horizontal amplifier output applies the sweep voltage to the horizontal deflection plates for horizontal deflection of the test signal across the crt screen.

The cathode ray tube and the negative high-voltage supply operate as previously described except that the intensity control is connected to the crt cathode rather than the control grid. The trace intensity is still controlled by varying the bias of the crt. The other dc power supplies function the same as those described in Figure 9. They also provide some additional voltages that are required for this oscilloscope.

TYPES OF MEASUREMENTS

Because an oscilloscope is not limited by a fixed calibrated scale, a mechanical pointer or a meter movement, it can be used to make different types of measurements. Basically, there are four types of measurements that can be made with most scopes. These are voltage, frequency, phase and distortion. All of these measurements are made by simply observing the pattern traced on the screen of a crt.

Voltage Measurements

The characteristics of an oscilloscope make it particularly well suited for the measurement of ac voltages. An ac test signal voltage is normally applied to the input of the vertical amplifier section. The electron beam is then deflected vertically by amounts that are proportional to the positive and negative peaks of the ac voltages applied to the vertical deflection plates. Thus, the height of the pattern on the screen is proportional to the peak-to-peak amplitude of the voltage applied to the vertical input terminals.

For accurate measurements, the scope must be calibrated. This is done by using either a known accurate external ac voltage source or a built-in source, such as the 1 volt peak-to-peak source shown near the bottom of the Power Supply Circuit Board in Figure 21. The calibration voltage is applied to the vertical input terminals and the vertical gain controls are adjusted so that the trace has a specified height on the crt screen.

coarse frequency control, instead of using different capacitors for each sweep rate change.

The circuit of the Horizontal Circuit Board is very similar to that of Figure 11. The Horizontal Circuit Board also has input protection, and the stability of the amplifier is increased by degenerative feedback. The horizontal amplifier output applies the sweep voltage to the horizontal deflection plates for horizontal deflection of the test signal across the crt screen.

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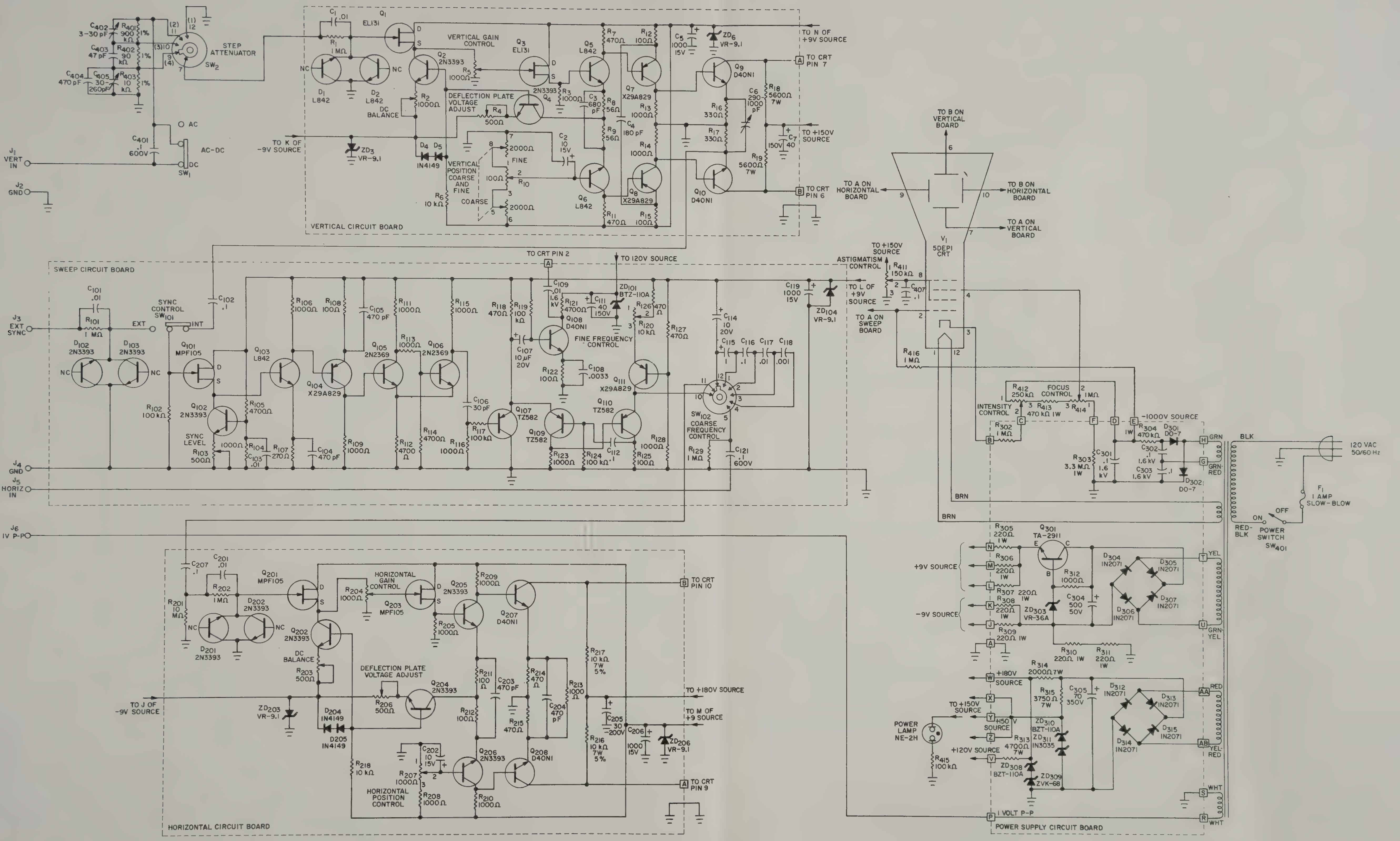

STEP ATTENUATOR
SW2
AC-DC
SW1
J1 VERT IN
J2 GND
VERTICAL GAIN CONTROL
DC BALANCE
DEFLECTION PLATE VOLTAGE ADJUST
VERTICAL POSITION COARSE AND FINE
FINE
COARSE
TO K OF -9V SOURCE
TO N OF +9V SOURCE
TO CRT PIN 7
TO +150V SOURCE
TO CRT PIN 6
VERTICAL CIRCUIT BOARD
TO B ON VERTICAL BOARD
TO A ON HORIZONTAL BOARD
TO B ON HORIZONTAL BOARD
TO A ON VERTICAL BOARD
V1 5DEP1 CRT
TO +150V SOURCE
ASTIGMATISM CONTROL
TO L OF +9V SOURCE
TO A ON SWEEP BOARD
TO CRT PIN 2
TO 120V SOURCE
SWEEP CIRCUIT BOARD
J3 EXT SYNC
SYNC CONTROL SW101
EXT
INT
SYNC LEVEL
FINE FREQUENCY CONTROL
SW102 COARSE FREQUENCY CONTROL
J4 GND
J5 HORIZ IN
J6 1V P-P
INTENSITY CONTROL
FOCUS CONTROL
-1000V SOURCE
120 VAC 50/60 Hz
F1 1 AMP SLOW-BLOW
POWER SWITCH SW401
ON
OFF
GRN
BLK
RED
BRN
YEL
WHT
+9V SOURCE
-9V SOURCE
+180V SOURCE
TO +150V SOURCE
150V SOURCE
+120V SOURCE
POWER LAMP NE-2H
1 VOLT P-P
POWER SUPPLY CIRCUIT BOARD
HORIZONTAL GAIN CONTROL
DC BALANCE
DEFLECTION PLATE VOLTAGE ADJUST
HORIZONTAL POSITION CONTROL
TO CRT PIN 10
TO +180V SOURCE
TO M OF +9 SOURCE
TO CRT PIN 9
TO J OF -9V SOURCE
HORIZONTAL CIRCUIT BOARD

Figure 21

This generator produces either a sinewave or a square wave from 20 Hz to 200 kHz. In conjunction with an oscilloscope, it is very useful for checking the frequency response of audio amplifiers.

Courtesy RCA-Electronic Components

The calibration voltage is then removed and as long as the vertical gain control remains unchanged, any unknown signal applied to the vertical input will produce a pattern on the crt screen, whose height can be correlated to the calibration signal.

The height comparison is normally made on a scope graticule. The graticule, sometimes referred to as a grid or recticule, is often a flat transparent plastic plate which is placed in front of the crt screen. The plate is usually divided into equal units (normally centimeters) vertically and horizontally. The calibration voltage and the unknown voltage are then compared in centimeters.

As an example assume, that an oscilloscope is calibrated so that a 1 volt peak-to-peak vertical input produces a trace with a height of 1 centimeter on the screen. If an unknown voltage applied to the vertical amplifier section produces a pattern that measures 4 centimeters peak-to-peak the amplitude of the unknown voltage is 4 volts peak-to-peak. This is because each centimeter of vertical deflection represents a peak-to-peak voltage of 1 volt.

Since the input step attenuator changes the test signal in exact steps, it can be used to expand the range of voltage measurements. Assume that the calibration was accomplished while using an attenuation factor of 1. If an unknown input signal then deflects the trace pattern beyond the top and bottom of the screen, the step attenuator must be reset to reduce the amplitude of the pattern to fit the screen. If this is accomplished when the step attenuator is reset to the position that attenuates the signal by a factor of 10, and the pattern is 4 centimeters high, then the unknown voltage is equal to 40 volts. This is because each centimeter of vertical deflection now represents a peak-to-peak voltage of 10 volts.

The oscilloscope shown in Figure 21 uses dc coupling; therefore, it can be used to measure dc voltages as well as ac voltages. However, the scope must again be appropriately calibrated. To do this, the step attenuator is first set to the ground position. Then, using the vertical position control, the trace (now a horizontal line) is positioned at the center of the graticule. The calibration is then performed in the same manner as for ac, except that the AC-DC switch must be set to the DC position, and a dc calibration voltage is applied to the vertical input. Now when an unknown dc voltage is connected to the vertical input, the trace is deflected up or down to a position that is proportional to the amplitude of the input voltage, and relative to the calibration voltage.

As an example, assume that the trace is adjusted for a vertical deflection of one centimeter when a +9 volt dc calibration voltage is applied. If the unknown voltage then deflected the trace up 2 centimeters the voltage would be +18 volts, and if the unknown voltage deflected the trace down 3 centimeters the voltage would be −27 volts. This is because each centimeter of deflection represents 9 volts and the direction represents the polarity.

The oscilloscope can also be used to measure the gain of an amplifier or other electronic devices. Gain measurements are made by comparing the amplitude of the output waveform to the amplitude of the input waveform. For example, assume that a scope is connected to the grid of an amplifier tube, and a waveform with a peak-to-peak amplitude of 1 cm appears on the graticule when the amplifier is carrying a normal signal. The scope is then connected to the plate of the amplifier tube, and a waveform with a peak-to-peak amplitude of 6 cm appears on the graticule. The output waveform is 6 times larger than the input waveform, so the amplifier voltage gain is 6.

This wide band 5" scope includes a built-in voltmeter directly under the crt screen. The meter may be used in calibrating the screen for peak-to-peak voltage measurements.
Courtesy Bach-Simpson Ltd.

Frequency Measurements

An oscilloscope can also be used to measure frequency. The simplest way to measure frequency is to use the internally generated sweep voltage as a standard. With the unknown frequency applied to the vertical input terminals and the SYNC CONTROL set to INT, adjust the coarse and the fine frequency controls for a stationary pattern on the screen. The pattern will be stationary when the unknown frequency is a multiple of the sweep frequency. To find the unknown frequency, multiply the number of cycles on the screen by the frequency of the horizontal sweep generator. For example, if the sweep generator of the scope is set at 1000 Hz and two cycles of a test signal appear on the screen, the frequency of the test signal must be 1000 × 2 = 2000 Hz.

This is an easy method of checking frequency, but its accuracy depends on the quality of the oscilloscope being used. The sweep controls on an oscilloscope usually are not accurately calibrated, so the sweep generator frequency used in the calculation is only approximate.

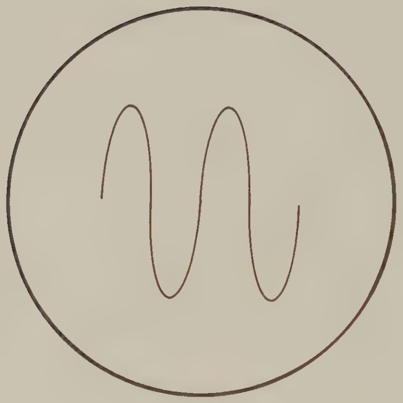


Figure 22

A more accurate frequency measurement may be obtained by comparing the trace pattern of the unknown frequency signal to the pattern produced by an accurately calibrated signal generator output. The unknown test signal is applied to the vertical input, the SYNC CONTROL set to INT, and the sweep frequency controls adjusted until one or more complete cycles appear on the crt screen. When these adjustments are made, the SYNC LEVEL control should be set at zero so that the sweep generator is free running, and only the sweep frequency controls used to stop the pattern on the screen. This pattern might look like the one shown in Figure 22.

The number of cycles on the screen should be counted now. Without touching the sweep frequency controls, the test signal is removed from the vertical input, and the output of the signal generator is applied to the vertical input of the scope. The signal generator frequency control is adjusted until the same number of cycles appears on the crt as when the unknown signal was applied. This means that the signal generator frequency is the same as the frequency of the unknown signal. You can determine this frequency by simply reading the dial on the signal generator.

Another method of frequency measurement is to interpret various patterns which are produced on the crt when sinewaves are applied to each set of deflection plates. These patterns are called **LISSAJOUS FIGURES.** Frequency ratios may be obtained from these patterns. By knowing the frequency of one of the voltages, the frequency of the other voltage may be found.

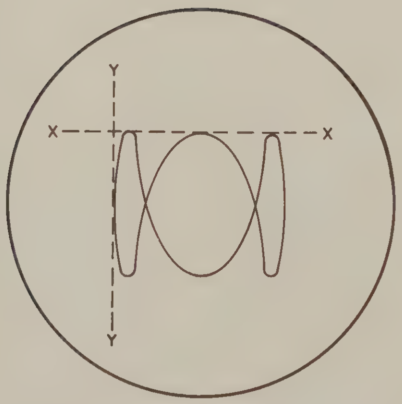


Figure 23

The scope horizontal sweep generator is not used in this method of frequency measurement. The Coarse Frequency Control is switched to the external input position (EXT IN). Then, the unknown test signal is applied to the vertical input and the known frequency signal is applied to the horizontal input. The pattern produced on the screen may be like that shown in Figure 23.

The frequency ratio of the vertical to the horizontal signal voltage is equal to the ratio of the number of points at which the Lissajous pattern touches the line labeled X-X to the number of points touching the line labeled Y-Y in Figure 23. When a voltage of known frequency is applied to the horizontal input, you can find the unknown frequency by dividing the number of loops touching line X-X by the number of loops touching line Y-Y and multiplying the result by the horizontal input frequency. That is:

$$f_v = f_h \times \frac{\text{loops touching X-X}}{\text{loops touching Y-Y}}$$

where f_h is the horizontal input frequency and f_v is the vertical input frequency.

Let's use Figure 23 to illustrate this system of frequency measurement. Three complete loops are touching the horizontal line X-X, and one loop touches the vertical line Y-Y. Suppose that the frequency of the signal applied to the horizontal input is 1000 Hz. In this case, the frequency of the vertical input signal would be $f_v = 1000 \text{ Hz} \times {}^3/_1 = 3000 \text{ Hz}$.

As the frequency ratio increases, it becomes more difficult to interpret the figures. Usually a ratio of 10 to 1 is about the largest ratio that can be easily read. The main problems in using Lissajous figures are in obtaining two voltages whose frequencies have an exact whole-number relationship to each other and whose frequencies do not drift. If either frequency drifts, the pattern will be in constant motion.

Phase Measurements

In the design or maintenance of electronic equipment, it may be necessary to make phase measurements of voltages or currents. These phase measurements are made by comparing two ac voltages of the same frequency and noting their relationship to each other.

To measure phase angle, one signal is applied to the vertical amplifier and the other signal is applied to the horizontal amplifier. The horizontal and vertical gain controls are then adjusted so that the horizontal and vertical deflection are equal. The result is a Lissajous pattern on the screen. Figure 24 shows some typical Lissajous patterns obtained by comparing sinewave signals of various phases.

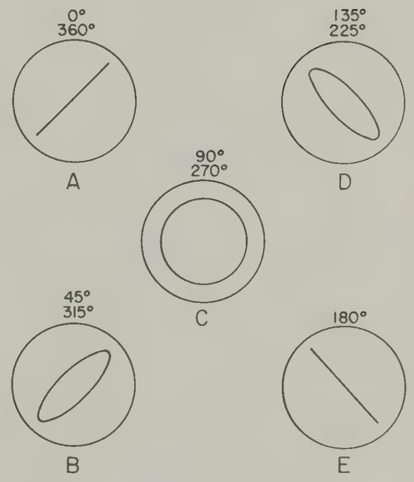


Figure 24

When two signals are in phase, a straight line, slanted to the right (or to the left, depending on the construction of the scope), will be produced. This pattern is shown in Figure 24A. Figure 24B shows the pattern for two signals that are 45 degrees out-of-phase with each other. Two signals 90 degrees out-of-phase produce a circle, as in Figure 24C. The pattern of Figure 24D is the result of two signals 135 degrees out-of-phase, and the straight diagonal line of Figure 24E is the result of a phase difference of 180 degrees. Depending upon the scope design, all of the slanted patterns will be either as shown in Figure 24 or they will all have the opposite slopes. The patterns obtained from the scope of Figure 21 slant as shown in Figure 24.

Notice that the trace changes from a diagonal line to an elliptical pattern that widens into a circle, and then becomes elliptical and ends up as a diagonal line in the opposite direction, as the phase angle is increased from 0 degrees to 180 degrees. If the angle is increased from 180 to 360 degrees, the pattern goes through the same changes in reverse order, from Figure 24E back to Figure 24A.

Distortion

Any unwanted change in the signal being amplified or coupled from one stage to another is called **DISTORTION.** Because an oscilloscope displays the actual waveform of the signal under test, it is an excellent device for detecting distortion. To determine if electronic equipment is distorting a signal, first observe the input signal on the oscilloscope screen. Then observe the output signal. In an amplifier, the output may be much greater in amplitude than the input, but it should have the same shape as the input waveform. Any difference between the shape of the input and output signals, other than a phase inversion, indicates some form of distortion.

If distortion is present in a multi-stage amplifier, the stage producing the distortion can be found by examining the input and output waveforms of each stage. Additional tests, such as voltage and resistance measurements, can then be used to find the cause of the distortion within the stage.

SUMMARY

The oscilloscope is a very useful test instrument. It can be used to display circuit waveforms when designing or troubleshooting electronic equipment. It can be used as a dc or peak-to-peak ac voltmeter. It can also be used to measure phase shift and determine unknown frequencies.

The heart of an oscilloscope is a cathode ray tube. A crt has an electron gun to produce an electron beam, a deflection section to deflect the beam and a screen to view the movement of the beam. Most scopes use crt's with electrostatic deflection and focusing. In this tube type, the electron beam is focused by the electrostatic field between gun electrodes, and the electrostatic fields between the deflection plates deflect the beam vertically and horizontally on its path to the screen.

Images are produced when electrons strike the phosphor coating that serves as the screen. The energy from the high speed beam electrons is changed to

The following Practice Exercise questions cover the subjects which you have just studied. They are:

SYNCHRONIZATION

SLOPE TRIGGER CIRCUIT

COMPLETE OSCILLOSCOPE SCHEMATIC

TYPES OF MEASUREMENTS

VOLTAGE MEASUREMENTS

FREQUENCY MEASUREMENTS

PHASE MEASUREMENTS

DISTORTION

49. With an oscilloscope, a synchronizing signal is normally applied to the (a) horizontal amplifier, (b) vertical amplifier, (c) horizontal sweep generator.

50. A sync signal replaces the horizontal sweep circuit in an oscilloscope. True or False?

51. What is the purpose of the sync amplitude control in an oscilloscope?

52. Changing the setting of SW_2 from the position shown in Figure 21 to position 2 will cause the amplitude of the signal applied to Q_1 to (a) increase, (b) decrease.

53. In the circuit of Figure 21, a positive-going signal on one of the vertical deflection plates is accompanied by a negative-going signal on the other vertical deflection plate. True or False?

54. What are the functions of SW_{102} and R_{120} in Figure 21?

55. Which control would you adjust in the circuit of Figure 21 to increase the amount of horizontal sweep?

56. Which control would you adjust in the circuit of Figure 21 to move the pattern from side to side on the screen?

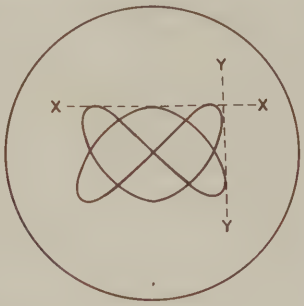
57. R_{414} in Figure 21 serves as the (a) intensity control, (b) focus control, (c) spot shape control.

58. In the high-voltage supply circuit of Figure 21, is the V_1 grid positive or negative with respect to the V_1 cathode?

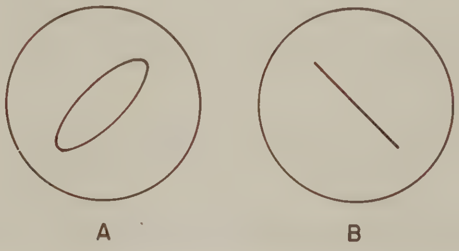
59. How is an oscilloscope calibrated to measure peak-to-peak voltage?

60. When Lissajous figures are used for frequency measurement, both the unknown and known frequencies are applied to the vertical input terminals. True or False?

61. Suppose that a 6000-Hz signal were applied to the horizontal input of an oscilloscope. What would be the frequency of a signal applied to the vertical input if the following pattern appears on the screen?



62. What phase relationships are illustrated by the following Lissajous patterns?



63. Why is an oscilloscope an excellent means of detecting distortion?

light energy as the electrons hit the phosphors. There are many types of phosphor materials, each with its own characteristics. One important characteristic is persistence, which refers to the length of time that the screen glows after it is struck by the electron beam. Another characteristic is the color of light given off by the screen.

Circuits in an oscilloscope provide the signals that control the crt electron beam movement. An oscilloscope horizontal sweep section is used to provide a linear horizontal time base for the crt. This results in a signal that deflects the beam horizontally across the screen at an even or linear rate. The test signal is applied to the vertical input of the scope, and a portion of the signal is used to trigger the sweep section. The sweep section is used to select and amplify the synchronizing signals to maintain a stationary pattern on the screen. An external trigger may also be used. When the frequency of the input signal is equal to some whole-number multiple of the horizontal sweep frequency, the image on the screen of the crt is stationary.

The output signals of the vertical and horizontal amplifiers are applied to the deflection plates to deflect the electron beam. Depending on the combination of voltages on the deflection plates, the electron beam of the crt may be moved to any point on the screen, tracing out a pattern of the test signal.

The power supply of a scope is made up of two sections: the low-voltage power supply and the high-voltage power supply. The low-voltage supply furnishes voltages for all stages. The high-voltage supply furnishes voltages for the electrodes of the crt.

Many practical measurements can be made by general purpose oscilloscopes. The general purpose oscilloscopes described in this lesson are suitable for most measurements of amplifier gain, frequency response, distortion and phase relationship. Some scopes are more specialized, designed to handle particular types of applications.

APPENDIX
TYPICAL PHOSPHOR CHARACTERISTICS

PHOSPHOR	COLOR	PERSISTENCE	APPLICATION
P1	Green	Medium	Radar, oscilloscopes
P2	Green	Medium	Oscilloscopes
P4	White	Medium	TV picture tubes
P5	Blue	Medium-Short	Photographic, recording
P7	Yellow	Medium-Long	Radar, oscilloscopes
P11	Blue	Medium-Short	Photographic, recording, oscilloscopes
P12	Orange	Long	Radar
P14	Orange	Medium	Military displays
P15	Green	Very short	TV cameras
P16	Violet	Very short	TV cameras
P17	Yellow	Long	Military displays
P19	Orange	Long	Radar
P21	Orange	Long	Radar
P22	Three-color	Medium	Color TV picture tubes
P23	White	Medium	TV picture tubes
P24	Green	Short	TV cameras
P25	Orange	Medium	Military displays
P26	Orange	Very long	Radar
P27	Orange	Medium	Color TV monitors
P28	Green	Long	Radar
P29	Two-color	Medium	Aircraft instruments
P31	Green	Medium-Short	Oscilloscopes
P32	Green	Long	Radar
P33	Orange	Very long	Radar
P34	Green	Very long	Radar, oscilloscopes

IMPORTANT DEFINITIONS

ACCELERATING ANODE—An electrode normally operated at a high positive potential to increase the velocity of electrons in the electron beam. Also referred to as the SECOND ANODE.

AQUADAG—A conductive material applied to the inside of the envelope of a cathode ray tube. The aquadag coating is an extension of the accelerating electrode and is also used to collect electrons that have struck the phosphor screen.

ASTIGMATISM CONTROL—An oscilloscope control used to obtain proper focus of the beam at all positions on the crt screen. This control usually varies the voltage on the accelerating anode of the crt. Also called a SPOT SHAPE CONTROL.

ATTENUATION—The process of reducing the level of a signal.

ATTENUATOR—A component or network of components used to reduce the level of a signal.

BRIGHTNESS CONTROL—In an oscilloscope, the control that varies the brightness, or intensity, of the image on the screen. It usually varies the dc difference of potential between the cathode and control grid. Also called an INTENSITY CONTROL.

CASCADE SCREEN—A screen that has more than one layer of phosphors to obtain a certain light characteristic. For example, two phosphors may be combined to obtain the characteristics of high light output and long persistence.

CATHODE RAY OSCILLOSCOPE—An electronic instrument consisting of a cathode ray tube and its associated circuits, used to produce a visual display of the voltage applied to its input.

CATHODE RAY TUBE (crt)—A vacuum tube in which electrons are formed into a beam and used to draw, or trace, an image of some desired pattern on a phosphor screen. The movement of the electron beam produces an image as in TV picture tubes, radar indicators and oscilloscope indicators.

COARSE FREQUENCY CONTROL—A control which varies the frequency of the oscilloscope horizontal sweep generator in large steps. It is usually a multiposition switch which selects one of a number of capacitors to control the sweep frequency.

DEFLECTION FACTOR—An expression that indicates the signal voltage required at the scope vertical input terminals to deflect the crt beam vertically one graticule division (1 inch, 1 centimeter, etc.). It is also an

IMPORTANT DEFINITIONS (Continued)

indication of how much voltage is required between a set of deflection plates to deflect the crt beam a specified distance.

DEFLECTION PLATES—In an electrostatic deflection system, the plates mounted inside the tube envelope used to deflect the electron beam across the crt screen.

DEFLECTION SENSITIVITY—An indication of how far the spot or image on the screen is deflected vertically for a signal at the vertical input terminals of a specified amplitude. It is also an indication of how far the crt beam will be deflected with a specified voltage between a set of deflection plates.

DISTORTION—Any unwanted change in the signal being amplified or coupled from one stage to another.

ELECTRON GUN—The group of electrodes in a crt that supplies the electrons, forms them into a beam, directs them along the tube axis and accelerates them so that they hit the phosphor screen with enough force to cause the phosphor to emit light.

ELECTROSTATIC DEFLECTION—A deflection system that uses varying electric potentials on a set of deflection plates to deflect the electron beam to any point on the crt screen.

FINE FREQUENCY CONTROL—A continuously variable control which varies the frequency of the horizontal sweep signal in an oscilloscope. It is usually a potentiometer that provides continuously variable frequency control within the range selected by the coarse frequency control.

FIRST ANODE—See FOCUSING ANODE.

FLUORESCENCE—The emission of light by a substance only during excitation. An example of fluorescence is the light emitted at the time that the screen phosphors are struck by the beam electrons.

FOCUS ANODE—An electrode to which a potential is applied to electrostatically control the focusing of the electron beam. Also referred to as the FIRST ANODE.

FOCUS CONTROL—A control used to focus the electron beam to produce a small spot on the screen of a crt. This control usually changes the voltage on the focus anode of the crt to vary the difference of potential between the focus anode and the accelerating anode.

FREQUENCY VERNIER CONTROL—See FINE FREQUENCY CONTROL.

IMPORTANT DEFINITIONS (Continued)

HORIZONTAL AMPLITUDE CONTROL—A control used to vary the amplitude of the horizontal sweep signal applied to the horizontal deflection plates of a crt. Also called a HORIZONTAL GAIN CONTROL or WIDTH CONTROL.

HORIZONTAL GAIN CONTROL—See HORIZONTAL AMPLITUDE CONTROL.

HORIZONTAL POSITIONING CONTROL—A control used to shift the beam from side to side, and thus shift the pattern horizontally on the screen of a crt.

HORIZONTAL SWEEP CIRCUIT—A circuit that produces a sawtooth voltage to sweep the beam from side to side at a linear rate on the screen of a crt. The circuit that provides a linear time base for the oscilloscope when a waveform is to be viewed on the screen.

INTENSITY CONTROL—See BRIGHTNESS CONTROL.

LISSAJOUS FIGURES—Patterns obtained when sinewaves of different frequency or phase are applied to the vertical and horizontal inputs of an oscilloscope.

LUMINESCENCE—The emission of light by a substance due to the absorption of energy. An example is the light emitted by a phosphor material which is struck by fast moving electrons.

PERSISTENCE—The measure of the length of time that a phosphor glows after it has been struck by an electron. The longer the persistence, the longer the phosphor glows after it is initially struck.

PHOSPHOR—A material that emits light when struck by electrons. The material that forms the screen of the crt.

PHOSPHORESCENCE—The emission of light which persists for a time after electrons strike the phosphor screen.

SCREEN—The phosphor coating on the face of a crt, which is excited by the electron beam, producing the visible pattern.

SECOND ANODE—See ACCELERATING ELECTRODE.

SLOPE SWITCH—Normally, a two position switch that selects the start of the trace pattern on the positive or negative slope of the test signal. Also referred to as the SLOPE TRIGGER SELECTOR.

SLOPE TRIGGER SELECTOR—See SLOPE SWITCH.

IMPORTANT DEFINITIONS (Continued)

SPOT SHAPE CONTROL—See ASTIGMATISM CONTROL.

STEP ATTENUATOR—A switch-type control that varies the amount of signal attenuation in steps, as compared to the smooth, continuously variable control of a potentiometer.

SWEEP TRIGGER LEVEL CONTROL—See SYNC AMPLITUDE CONTROL.

SYNC AMPLITUDE CONTROL—A control that varies the amplitude of the synchronizing signal applied to the horizontal sweep generator of an oscilloscope. Sometimes called SWEEP TRIGGER LEVEL CONTROL.

SYNC SELECTOR SWITCH—A switch used to select the source of the synchronizing signal fed to the horizontal sweep generator of an oscilloscope. In many scopes, a two position switch which permits selection of a sync signal from either the vertical amplifier circuit or from some external source. Commonly referred to as the SYNC SWITCH.

SYNC SIGNAL—See SYNCHRONIZING SIGNAL.

SYNC SWITCH—See SYNC SELECTOR SWITCH.

SYNCHRONIZING SIGNAL—A signal used to keep the horizontal sweep generator of an oscilloscope in step with the waveform to be viewed. This signal ensures that the sweep generator begins a cycle of oscillation at the same time that a cycle of the test waveform begins so that the pattern remains stationary on the screen. Usually referred to as the SYNC SIGNAL.

TRACE—The pattern produced on the screen of a crt by the movement of the electron beam.

VERTICAL AC-DC SWITCH—Normally, a two position switch set for either viewing or eliminating the dc component of the test signal.

VERTICAL AMPLITUDE CONTROL—A control used to vary the amplitude of the signal applied to the vertical deflection section of a crt. Also called a VERTICAL GAIN CONTROL.

VERTICAL GAIN CONTROL—See VERTICAL AMPLITUDE CONTROL.

VERTICAL POSITIONING CONTROL—A control used to shift the beam up and down, and thus shift the pattern vertically on the screen of a crt.

WIDTH CONTROL—See HORIZONTAL AMPLITUDE CONTROL.

PRACTICE EXERCISE SOLUTIONS

1. The basic purpose of a cathode ray tube is to display a picture whose shape is determined by voltages applied to the tube.

2. By changing the deflection voltages across the crt deflection plates.

3. The three main sections of a crt are: the electron gun, the deflection section and the screen.

4. (c) electron gun.—The deflection plate voltages cause the electron beam to move up or down and left or right, while the screen shows a picture by luminescence—the giving off of light.

5. The electron beam is bent, or caused to move from its normal path, by the deflection section.

6. screen or face—The screen consists of a material that gives off light when it is struck by fast-moving electrons.

7. The five electron gun elements are: the heater, cathode, control grid, first anode and second anode.

8. The cathode emits the electrons that form the electron beam. The control grid controls the number of electrons that will make up the electron beam. The first anode is used to focus the electron beam so that the trace of light appears sharp and clear on the crt screen.

9. The second anode, often called the accelerating anode or accelerating electrode.

10. False—The second anode is normally operated at a high positive potential with respect to the cathode.

11. False—Electrostatic lines of force exist only between points that are at different potentials.

12. True

13. Besides helping to focus the electron beam, the second anode acts to accelerate the electrons in the beam.—This is because the high positive potential applied to this anode attracts the negatively charged electrons.

14. To change the focus of an electron beam, the voltage on the first anode is varied.

15. The graphite coating on the inside of the crt envelope is called aquadag. It is part of the second anode and helps maintain a uniform accelerating field. It also collects the electrons after they strike the screen.

PRACTICE EXERCISE SOLUTIONS (Continued)

16. Luminescence.—The screen is coated with a phosphor material which gives off light whenever it is exited (struck) by moving electrons.

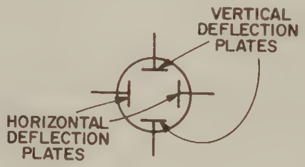
17. The term fluorescence refers to light given off while the screen phosphor is being struck by electrons. Phosphorescence is a term applied to any light given off by the phosphor after it is struck by the electron beam.

18. The phosphors on the 5UP1 screen provide medium persistence and produce a green image. The image of the 5UP1 is the same color and has the same persistence as that of the 5BP1. Both types are 5 inch tubes and both have P1 phosphor screens.

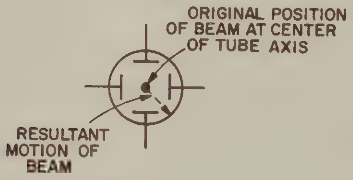
19. A set of charged plates attracts or repels an electron because of the interaction between the charges on the plates and the negative charge on the electron.

20. The horizontal deflection plates shown in Figure 6 cause the electron beam to move right or left across the crt screen.

21.



22. The electron beam would be forced downward and to the right. The lower vertical deflection plate and the right horizontal deflection plate attract the electron beam.



23. Deflection sensitivity is an indication of how far the spot moves vertically on the crt screen for each volt applied to the scope's vertical input terminals. It is also an indication of how far the beam moves for a specified voltage between the deflection plates. These distances may be expressed in inches, centimeters or millimeters.

24. 5 inches per volt.

$$\frac{2.5 \text{ inches}}{0.5 \text{ volt}} = 5 \text{ inches per volt.}$$

PRACTICE EXERCISE SOLUTIONS (Continued)

25. Deflection factor indicates the voltage required at the scope's vertical input terminals to produce a certain deflection on the screen. It is also an indication of how much voltage is required between a set of deflection plates for a specified amount of beam deflection. It is the reciprocal of deflection sensitivity.

26. 0.2 volt per inch. Dividing 1 by the deflection sensitivity obtained in Practice Exercise 24; $^1/_5 = 0.2$ volt per inch.

27. The six sections are: the high-voltage power supply, the low-voltage power supply, the vertical amplifier section, the horizontal amplifier section, the horizontal sweep section and the cathode ray tube.

28. True

29. Signals applied to the horizontal deflection system move the spot from side to side on the crt screen.

30. (b) vertical amplifier system.

31. True

32. (b) focus anode.

33. The high-voltage power supply is usually connected to certain elements of the crt.

34. (b) negative.

35. True

36. A wide frequency response allows the vertical amplifier to reproduce waveforms with minimum distortion.

37. True—This avoids loading the test circuit and reduces distortion.

38. (b) 180° out-of-phase.—Q_5 and Q_6 of Figure 11 form a phase inverter stage, and therefore, the signal voltages on their collectors are 180° out-of-phase.

39. Positioning control.

40. Horizontal amplitude control, horizontal gain control or width control.

41. (b) less than the gain of the vertical amplifier.—Because the signal applied to this circuit is usually larger than that applied to the vertical input circuit, less gain is required to sweep the beam horizontally across the screen.

PRACTICE EXERCISE SOLUTIONS (Continued)

42. To overcome frequency discrimination due to the input capacitance of the amplifier.

43. False—A source follower does not provide a voltage gain. The purpose of Q_1 is to prevent loading of the test circuit, and also to reduce the effects of shunt capacitance.

44. True

45. (b) sawtooth.

46. (b) cut off.

47. The frequency would decrease.—If R_4 is set to a higher value, the sawtooth-forming capacitor must discharge through a higher resistance. This means it will take longer to discharge to where Q_2 cuts off, and there will be fewer sawtooth waveforms per second (lower frequency).

48. True—Capacitor C_2 discharges slower than it charges to produce the rising portion of the sawtooth during the time that Q_2 is cut off.

49. (c) horizontal sweep generator.

50. False—The horizontal sweep generator provides the sawtooth for the horizontal deflection plates. The sync signal merely keeps the generated sawtooth from drifting in frequency and phase.

51. To control the amount of sync voltage applied to the sweep generator.—The sync amplitude control should be advanced just far enough to hold the pattern stationary on the screen. Too strong a sync signal can trip the generator erratically and cause a highly distorted pattern on the screen.

52. (a) increase.—At the position shown in Figure 21, the input signal is attenuated by a factor of 100. At position 2 of SW_2 the attenuation factor is 1. That is, the full input signal is applied to Q_1.

53. True

54. SW_{102} serves as the coarse frequency switch. R_{120} is the fine frequency control.

55. R_{204}.—This potentiometer serves as a horizontal amplitude (width) control, and thus determines the amplitude of the sweep signal applied to the horizontal deflection plates.

56. R_{207}.—This potentiometer varies the dc base voltage at Q_{206}, which changes

PRACTICE EXERCISE SOLUTIONS (Continued)

the operating point of Q_{208}. This changes the dc voltage on the deflection plate connected to Q_{208}, causing the trace to shift horizontally.

57. (b) focus control.

58. Negative.—The voltage doubler circuit provides a negative output voltage for the bleeder network of resistors R_{412}, R_{413}, R_{414} and R_{303}. The control grid of V_1 returns through R_{416} to the output of the voltage supply, which is the most negative point in the circuit.

59. A known voltage is applied to the vertical input terminals, and the vertical gain controls are adjusted to produce a pattern of some convenient amplitude. Once the scope is calibrated, unknown voltages can be determined by measuring the amplitudes of the patterns they produce on the screen and comparing these amplitudes to that produced by the known voltage signal.

60. False—The unknown frequency is normally applied to the vertical input and the known frequency is applied to the horizontal input.

61. 9000 Hz.—There are three loops touching the X-X line, and two loops touching the Y-Y line. The vertical frequency is

$$f_v = 6000 \times \frac{3}{2} = 9000 \text{ Hz}.$$

62. (A) 45° or 315°; (B) 180°.

63. An oscilloscope shows the waveform of the signal under test. Any distortion in the wave is readily seen on an oscilloscope.

DE VRY INSTITUTE OF TECHNOLOGY
4141 BELMONT AVENUE, CHICAGO, ILLINOIS 60641

ONE OF THE
BELL & HOWELL SCHOOLS

7425A
EXAMINATION CHECK SHEET

1. A - IN A CRT, THE SECTION THAT SUPPLIES THE ELECTRONS, FORMS THEM INTO A BEAM, DIRECTS THEM TOWARD THE SCREEN AND ACCELERATES THEM SO THAT THEY HIT THE SCREEN AT A HIGH VELOCITY IS CALLED THE -- ELECTRON GUN.
The deflection plates control the position of the beam. The focusing anode and control grid are elements of the electron gun.

2. C - TO SHIFT THE POSITION OF THE ELECTRON BEAM IN AN ELECTROSTATIC DEFLECTION CRT, VARYING ELECTRIC POTENTIALS ARE APPLIED TO THE -- DEFLECTION PLATES.
The aquadag coating collects electrons after they have struck the screen; the cathode supplies the electrons for the beam; and the accelerating anode accelerates the electrons.

3. D - WHAT IS THE DEFLECTION SENSITIVITY IF A DEFLECTION VOLTAGE OF 3 VOLTS CAUSES THE SPOT TO MOVE A DISTANCE OF 0.3 INCH ON THE SCREEN OF A CRT? -- 0.1 INCH PER VOLT.
Deflection sensitivity is equal to

$$\text{Deflection sensitivity} = \frac{\text{Deflection Distance}}{\text{Deflection Voltage}}$$

$$= \frac{.3 \text{ inch}}{3 \text{ volts}}$$

$$= 0.1 \text{ inch per volt}$$

4. C - THE VOLTAGE DEVELOPED BY THE HORIZONTAL SWEEP SECTION IS APPLIED TO THE -- HORIZONTAL AMPLIFIER SECTION.
The horizontal sweep section develops a sawtooth voltage that must be amplified before being applied to the deflection plates.

5. B - IN MOST OSCILLOSCOPES, THE BRIGHTNESS OF THE IMAGE ON THE SCREEN IS VARIED BY CHANGING THE DC VOLTAGE BETWEEN THE -- CATHODE AND CONTROL GRID.
The screen brightness is determined primarily by the number of electrons striking the screen which, in turn, is controlled by the grid-cathode bias voltage.

6. A - THE HORIZONTAL SWEEP SECTION OF FIGURE 8 GENERATES -- A SAWTOOTH VOLTAGE.
The purpose of the horizontal sweep section is to generate a waveform that, when amplified and applied to the horizontal deflection plates, causes a relatively slow but linear trace and a relatively fast retrace. A sawtooth waveform fulfills these requirements.

7. B - IN FIGURE 21, THE INTERNAL SYNC SIGNAL IS OBTAINED FROM THE -- VERTICAL AMPLIFIER SECTION.
The internal sync signal is always obtained from the vertical amplifier section.

8. D - AN OSCILLOSCOPE IS CALIBRATED BY APPLYING 2 VOLTS PEAK-TO-PEAK TO THE VERTICAL INPUT AND ADJUSTING THE CONTROLS TO PRODUCE A DEFLECTION OF 4 CENTIMETERS. WHAT IS THE PEAK-TO-PEAK VALUE OF A TEST SIGNAL APPLIED TO THE VERTICAL INPUT THAT CAUSES A DEFLECTION OF 10 CENTIMETERS? -- 5 VOLTS.
Since 2 volts causes 4 centimeters of deflection, the calibration is 2 centimeters per volt. Therefore, 10 centimeters of deflection is produced by 5 volts.

9. A - THE CONTROLS OF AN OSCILLOSCOPE ARE SET SO THAT THE HORIZONTAL SWEEP GENERATOR IS OPERATING AT 1000 Hz. A TEST SIGNAL IS APPLIED TO THE VERTICAL INPUT, AND 4 CYCLES OF THIS SIGNAL APPEAR ON THE SCREEN. WHAT IS THE FREQUENCY OF THE TEST SIGNAL? -- 4000 Hz.
The frequency of the test signal is equal to the sweep frequency multiplied by the number of cycles. Thus, 1000 × 4 = 4000 Hz.

10. C - TWO SINEWAVES OF EQUAL FREQUENCY ARE APPLIED TO THE VERTICAL AND HORIZONTAL INPUT TERMINALS OF AN OSCILLOSCOPE. IF THE PATTERN ON THE SCREEN IS A CIRCLE, WHAT IS THE PHASE ANGLE BETWEEN THE TWO SINEWAVES? -- 90°.
In order to produce a circle on the crt screen, it is necessary that the two signals be phase separated by 90° or by 270°.

QUESTIONS

IMPORTANT—These instructions **MUST** be accurately followed to avoid loss, or errors in grading.

Indicate your answer on this sheet by filling in the box for the most correct answer to each question, as illustrated in the example below.

When all questions have been answered, place the answer card in the proper position to line up the boxes on the card with the boxes on the sheet.

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LESSON CODE
7425A

Example: A pulley is a
A ☐ B ☐ C ☐ D ■
(A) young hen. (B) railroad car.
(C) heating apparatus. (D) mechanical device.

1. A ☒ B ☐ C ☐ D ☐
In a crt, the section that supplies the electrons, forms them into a beam, directs them toward the screen and accelerates them so that they hit the screen at a high velocity is called the
(A) electron gun. (B) deflection plates. (C) focusing anode. (D) control grid.

2. A ☐ B ☐ C ☒ D ☐
To shift the position of the electron beam in an electrostatic deflection crt, varying electric potentials are applied to the
(A) aquadag coating. (B) cathode. (C) deflection plates. (D) accelerating anode.

3. A ☐ B ☐ C ☐ D ☒
What is the deflection sensitivity if a deflection voltage of 3 volts causes the spot to move a distance of 0.3 inch on the screen of a crt?
(A) 10,000 inches per volt. (B) 1.0 volt dc per inch. (C) 0.9 inch per volt. (D) 0.1 inch per volt.

4. A ☐ B ☐ C ☒ D ☐
The voltage developed by the horizontal sweep section is applied to the
(A) crt electron gun. (B) vertical amplifier section. (C) horizontal amplifier section. (D) power supply section.

5. A ☐ B ☒ C ☐ D ☐
In most oscilloscopes, the brightness of the image on the screen is varied by changing the dc voltage between the
(A) focus anode and accelerating anode. (B) cathode and control grid. (C) control grid and focus anode. (D) vertical deflection plates.

6. A ☒ B ☐ C ☐ D ☐
The horizontal sweep section of Figure 8 generates
(A) a sawtooth voltage. (B) a sinewave voltage. (C) the vertical deflection voltage. (D) an external sync signal.

7. A ☐ B ☒ C ☐ D ☐
In Figure 21, the internal sync signal is obtained from the
(A) crt filament. (B) vertical amplifier section. (C) horizontal amplifier section. (D) high-voltage power supply.

8. A ☐ B ☐ C ☐ D ☒
An oscilloscope is calibrated by applying 2 volts peak-to-peak to the vertical input and adjusting the controls to produce a deflection of 4 centimeters. What is the peak-to-peak value of a test signal applied to the vertical input that causes a deflection of 10 centimeters?
(A) 2 volts. (B) 1 volt. (C) 25 volts. (D) 5 volts.

9. A ☒ B ☐ C ☐ D ☐
The controls of an oscilloscope are set so that the horizontal sweep generator is operating at 1000 Hz. A test signal is applied to the vertical input, and 4 cycles of this signal appear on the screen. What is the frequency of the test signal?
(A) 4000 Hz. (B) 250 Hz. (C) 1000 Hz. (D) 4 Hz.

10. A ☐ B ☐ C ☒ D ☐
Two sinewaves of equal frequency are applied to the vertical and horizontal input terminals of an oscilloscope. If the pattern on the screen is a circle, what is the phase angle between the two sinewaves?
(A) 0°. (B) 60°. (C) 90°. (D) 120°.

QUESTIONS

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(A) 0°. (B) 60°. (C) 90°. (D) 120°.

ELECTRONIC DISPLAY DEVICES

7430

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Digital electronic displays are being used extensively in all areas of electronics. The accuracy of the test or measurement equipment, such as this digital thermometer, is greatly improved by using a digital display rather than analog-type meters.

Courtesy Hewlett Packard Co.

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You cannot depend on your eyes when your imagination is out of focus.

—Mark Twain

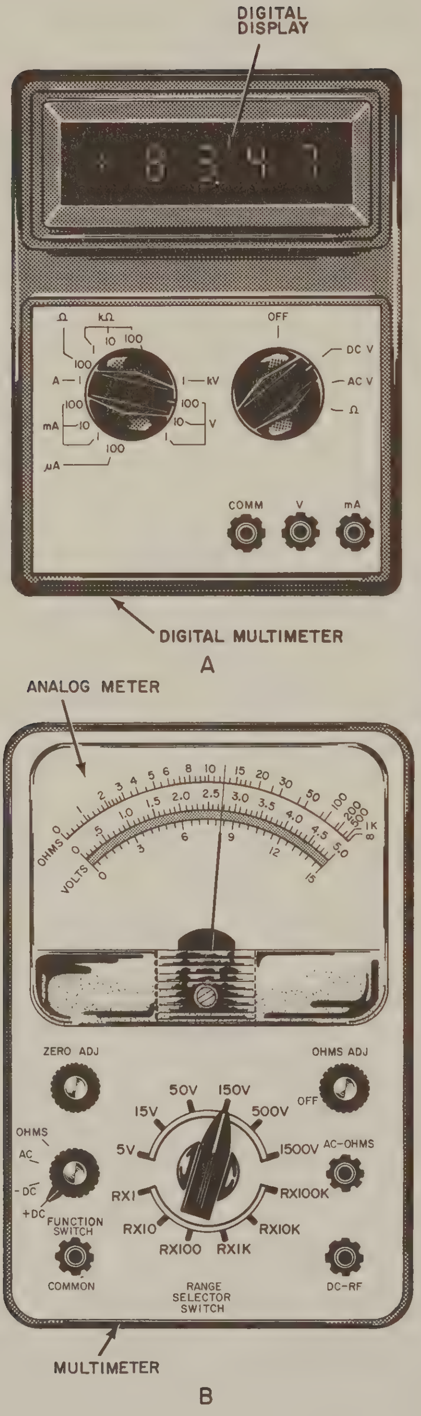


Figure 1

ELECTRONIC DISPLAY DEVICES

Expanding technology and considerable research in the vacuum tube and semiconductor fields have introduced a new form for displaying measured quantities. The new form involves a device known as a digital display. A digital display, like the one shown in Figure 1A, provides an extremely accurate indication of the measurement, which is much easier to read than the analog type of meter shown in Figure 1B. The digital display shows the value of the measurement as a group of numerals or digits. This type of display is also commonly referred to as a digital readout, digital indicator, or digital panel meter.

Digital displays have opened the door for the development of highly accurate measuring equipment such as the digital multimeter shown in Figure 1A. Measurement accuracy of .01% to .001% of full-scale indication is a result of the superior circuits used in the digital multimeter. The measurement accuracy of the multimeter shown in Figure 1B ranges from 3% to 1% of full-scale deflection, at best. In addition to measurement accuracy, another advantage of the digital multimeter is accuracy of the reading. The operator simply reads the numerals being displayed (Figure 1A) and does not have to estimate the value of the reading by the position of the pointer (Figure 1B) when it lies between the scale lines of the meter.

The digital display of Figure 1A consists of four single-digit displays or readout devices. Generally speaking, there are four classes of display devices which are commonly used. These display devices may be classified as mechanical, light transfer, light emitting and cathode ray tube (CRT). In this lesson, we will study at least one display device from each of these classes.

MECHANICAL DISPLAYS

A common mechanical display is the odometer in an automobile. It consists of six wheels, with numerals 0 through 9 on each wheel, which indicate the number of miles that the automobile has been driven. A similar display device, shown in Figure 2, is used in a tape recorder to count the number of revolutions completed by the tape reel. The three-digit display is driven by the counter belt. This belt moves as the tape reel of the recorder rotates and drives the counter pulley. The worm gear is connected to the shaft of the counter pulley and rotates with the pulley. As the worm gear rotates, it drives the display driver gear. This gear is attached to the units display and, when it rotates, the units display also rotates. With the counter belt rotating, the gears drive the units display to show the numerals 0 through 9. When the count of nine is reached, the index teeth (shown on the tens display) engage the index gear. As the units display continues to rotate, the numeral 0 appears. Simultaneously, the tens display advances one number (in arithmetic, this operation is generally called "the carry"). When the count of nine is reached on the tens display, the next index of the tens display resets it to 0 and advances the hundreds display by one number.

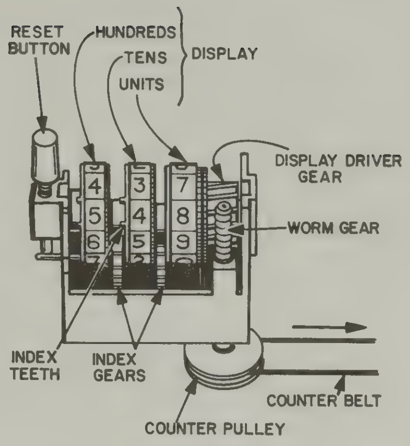


Figure 2

The mechanical counter and display of Figure 2 can be replaced by electronic circuits and digital display devices. The remainder of this lesson will describe the various types of electronic displays that are commonly used.

LIGHT TRANSFER DISPLAYS

The most common type of light transfer display device is the rear projection readout. The operation of this device is much the same as a slide projector. Figure 3 shows the construction of a rear projection readout device. Ten lamps allow the display of the numerals 0 to 9. The light from each of the incandescent lamps passes through a particular set of holes in the two light masks. These masks prevent the light from scattering and illuminating more than one numeral of the character mask. When light strikes the character mask, it passes through the transparent numeral of the mask and projects the numeral shape on the screen. This numeral shape is properly focused as it passes through the focus mask.

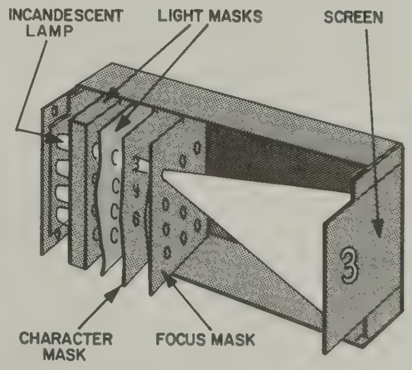


Figure 3

In Figure 3, the projection readout is shown displaying the numeral 3. If the numeral 6 must be displayed, the lamp for the 3 display must be turned off and the lamp which is used for the 6 display must be turned on. The light from that lamp shines through a different set of holes in the light masks, through numeral 6 of the character mask, through a different lens in the focus mask, and the 6 is displayed in the center of the screen. The individual lamps operate from external control circuits, which permit selection of the proper character for display.

The character that occupies each position of the character mask may be a numeral, a letter, a word or a message. This type of readout is particularly useful for displaying the units of measurement, such as volts, amps, ohms, rpm, etc., which are displayed by a panel meter.

One of the advantages of this type of display is that it is visible from greater viewing distances. Another advantage is that the incandescent lamps used in these displays usually are long-life lamps. Furthermore, the color of the display can be changed to suit the observer by placing a color filter over the screen.

This digital clock uses incandescent segment displays which produce a very bright readout that is readable in very high ambient light conditions.

Courtesy RCA Corporation

The greatest disadvantage of the projection readout is its physical size. The readout shown in Figure 3 is 6 inches long, 4 inches high and 3 inches wide. However, the size does vary, depending upon the required character size. For a larger character display, the length of the case must be increased. Another disadvantage of this type of display is its limited display rate. The display rate is the fastest rate at which the display may be changed from one character to another. The display rate is limited by the time required to heat the filament of one lamp so that it emits light, plus the time required to cool the filament of the other lamp so that no light is emitted. The average display has a typical display rate of five character changes per second. Finally, if a lamp is replaced, the new lamp may be brighter than the others. This causes one numeral to be displayed with greater intensity than the remaining numbers.

LIGHT-EMITTING DISPLAYS

A variety of known substances emit light when excited by an appropriate signal source. Examples of light-emitting substances are certain types of gases such as neon, the metal filament of an incandescent lamp, phosphor-coated electrodes, and the gallium arsenide phosphide (GaAsP) and gallium phosphide (GaP) compounds which are used in light-emitting diodes. We will now examine some typical light-emitting displays.

Gas Discharge Displays

One widely used gas discharge display is the Nixie tube, manufactured by Burroughs Corporation. The Nixie tube contains ten cathodes, one for each numeral, 0 through 9, as shown in Figure 4. Note that a pin is connected to the bottom of each cathode. These pins protrude from the bottom of the assembled tube envelope. Figure 5A shows the front view of an assembled tube. Notice that all of the cathodes appear to be sandwiched together. The side view, Figure 5B, shows that the cathodes are actually placed behind one another inside the glass envelope. Because each cathode is in a different plane (one behind the other), the Nixie tube is a **MULTIPLANAR DEVICE.**

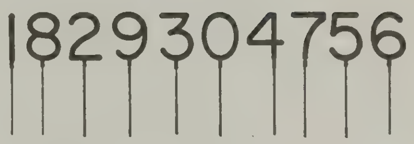
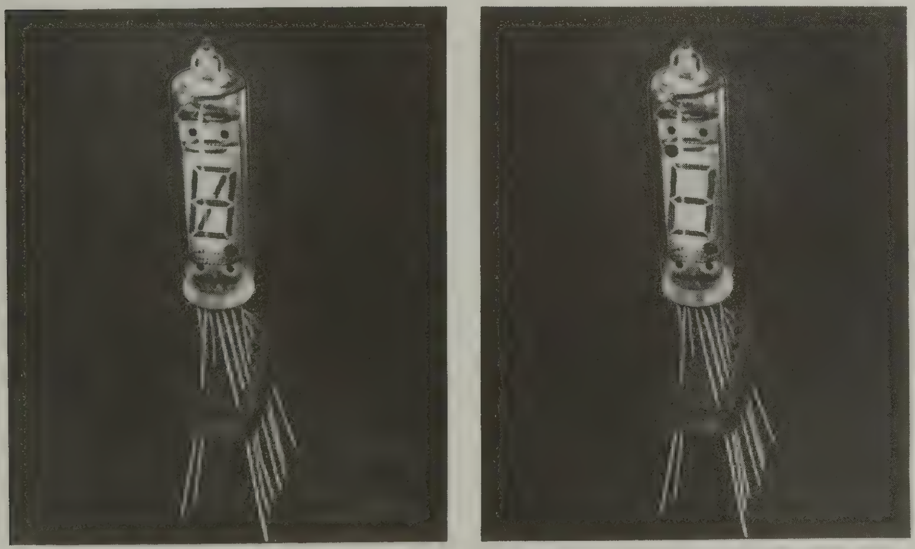


Figure 4



Cold cathode, gas discharge displays come in a variety of arrangements such as this seven-segment readout.
Courtesy Alco Electronic Products, Inc.

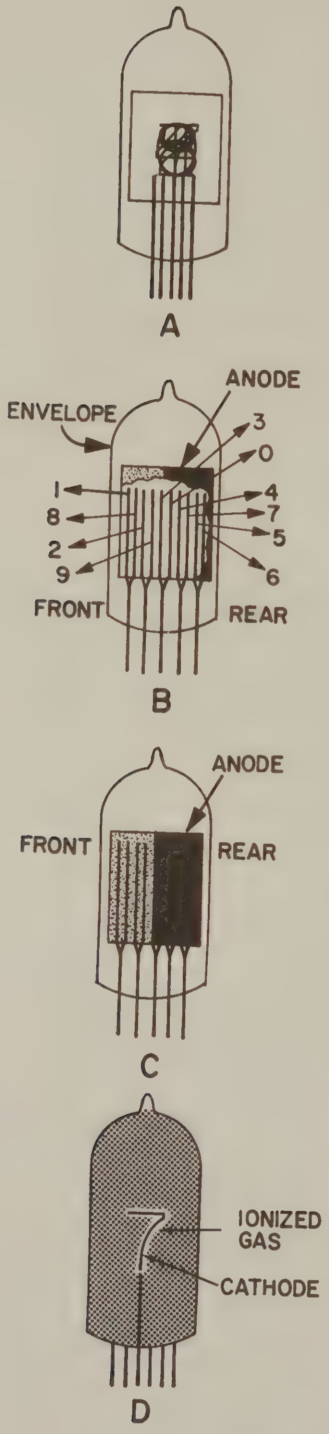


Figure 5

Figure 5C shows the tubular anode that completely surrounds the cathodes. The rear portion of the anode is solid, while the front half of the anode is a fine wire mesh which allows the observer to see the number being displayed.

The operation of the Nixie tube is quite simple. The cathodes are enclosed in the glass tube envelope, which is filled with neon. The cathodes have no filaments to heat them; therefore, the Nixie is referred to as a cold cathode display device. The anode is connected to a positive dc supply that can range from +120V dc to +200V dc. Through a switching arrangement, this constant current supply is then connected to the proper cathode to display a particular numeral. With both anode voltage and cathode current present, an electric field is created between that cathode and the anode. This electric field causes **IONIZATION** of the neon which is closest to the surface of the cathode. The ionized neon then emits light, as shown in Figure 5D. If more current were applied to the cathode, more of the neon would be ionized and the display would appear to be brighter.

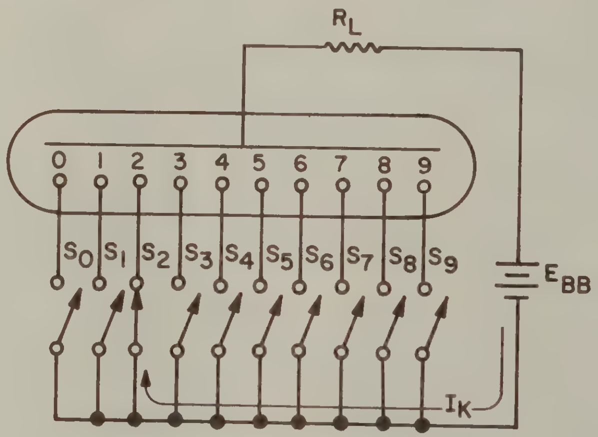


Figure 6

A simplified schematic of the multiplanar Nixie tube is shown in Figure 6. In practice, E_{BB} is actually a regulated dc power source for the Nixie display. The resistor (R_L) controls the cathode current and the operating voltage across the tube. When switch S_2 is closed as shown, current (I_K) is through the numeral 2 cathode; ionization of the neon occurs and the numeral 2 is displayed.

When compared to other types of displays, the gas discharge display offers an advantage of relatively low cost. Also, each numeral it displays is well defined and easily recognized. The display also has an extremely long life expectancy. Some of the original Nixie tubes manufactured in the middle 50's are still in operation. Finally, the device has a very fast display rate.

One of the disadvantages of the gas discharge display is the cost of the power supply. The power supplies used in most modern test and digital instruments are low-voltage circuits (5V dc to 24V dc); therefore, the extra cost of the additional supply (E_{BB} of Figure 6) is a disadvantage. Also, failure of a cathode prevents display of its associated numeral. Another disadvantage is the limited viewing angle caused by the multiplanar construction. The observer must be directly in front of the display to read each digit. The physical size of the tube is another disadvantage because it occupies more space than some other displays. When a gas discharge display is used in a sensitive receiver, another disadvantage occurs which, in other applications, might not be noticed. The ionization of the neon creates r-f noise, which may cause noticeable electrical interference if proper shielding is not used. Orange-red is the only available color of this display.

Incandescent Segment Displays

INCANDESCENCE, the operating principle of the incandescent lamp, is the basis for several currently available displays. One such display uses a number of filaments (called display segments), arranged to display any numeral from 0 through 9, as shown in Figure 7. Shown are seven display segments which are controlled by external circuits. Each segment emits light

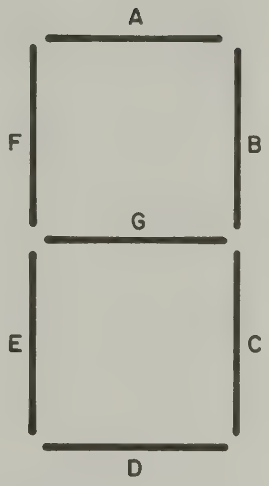
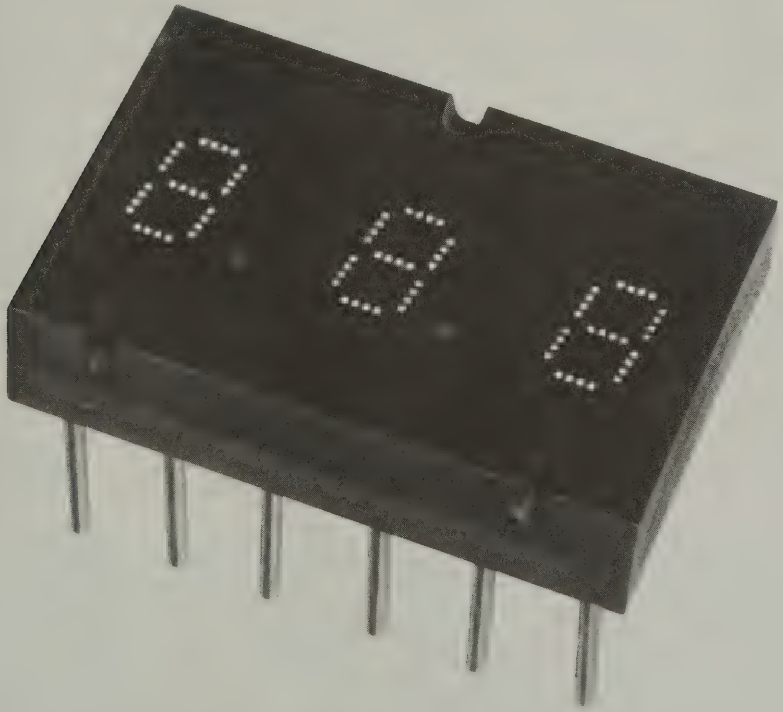


Figure 7



Multiple-digit, seven-segment LED displays conserve space, reduce cost and may have more than one diode junction per segment.

Courtesy Litronix, Inc.

when connected to an appropriate voltage source. Depending on the manufacturer, this voltage, called the segment voltage, may range from 2V dc to 5V dc. The display is normally packaged in an evacuated envelope (vacuum tube) to prevent the filaments from readily burning out.

NUMBER	SEGMENTS USED
0	A, B, C, D, E AND F
1	B AND C
2	A, B, G, E AND D
3	A, B, G, C AND D
4	F, G, B AND C
5	A, F, G, C AND D
6	A, F, E, D, C AND G
7	A, B AND C
8	ALL
9	A, F, G, B AND C

Figure 8

By lighting the proper display segments, numerals are formed and displayed. For example, the numeral 0 is formed by lighting display segments A, B, C, D, E and F. The numeral 1 is formed by lighting display segments B and C. The numeral 2 is formed by lighting display segments A, B, G, E and D. The display segments which must emit light to form each numeral are listed in Figure 8.

The display rate for this type of display can be increased by maintaining a small voltage across each display segment that is not used. The display segments are represented by the incandescent lamps labeled F_A through F_G, as shown in Figure 9. Resistors R_A through R_G maintain a small voltage across each unused display segment at a value that is less than that required for incandescence. When a numeral is selected for display, the limiting resistor for each segment required to display that numeral is shorted by the appropriate switch and those segments emit light. For the conditions shown in Figure 9, the numeral 1 is displayed.

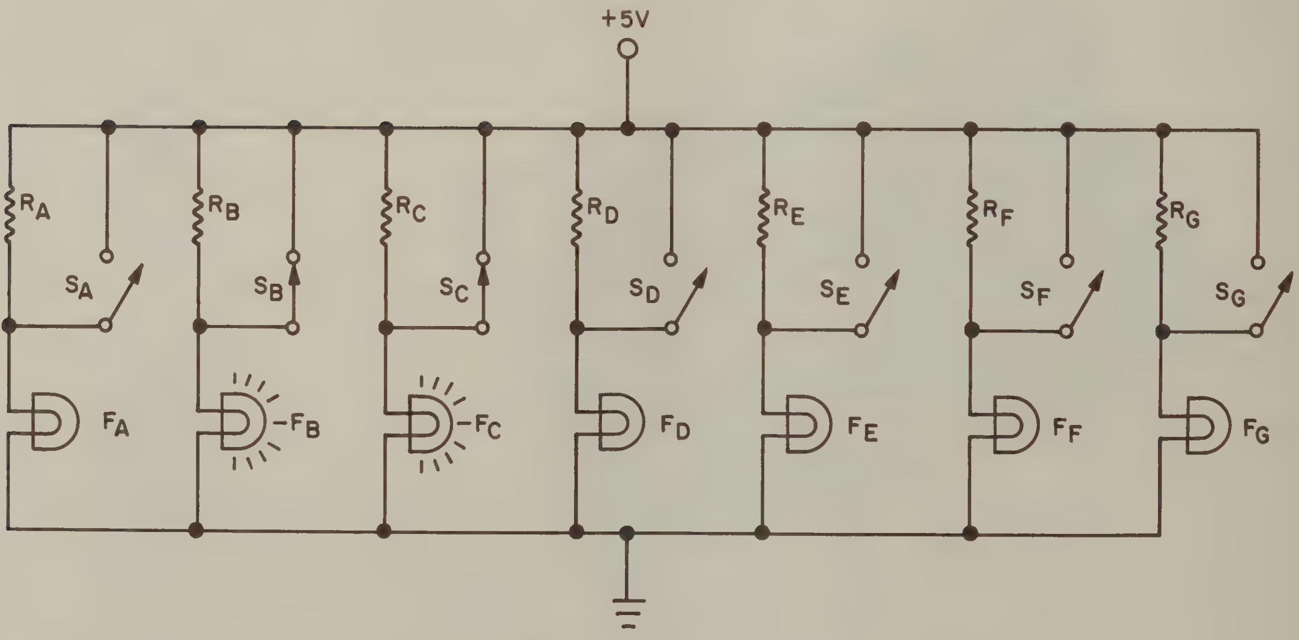


Figure 9

This type of display has a life expectancy of approximately 100,000 hours. An advantage of this display over the gas discharge display is that an additional high-voltage power supply is not required. Another advantage is that this display will operate over a wide temperature range (−50° C to +125° C). Because the display is constructed in a single plane, it is referred to as a **PLANAR** display. When this type of display is used, the observer does not have to stand directly in front to view each digit (as required with the multiplanar display). Also, this display is very bright and may be viewed easily even in direct sunlight.

A disadvantage of this type of display (as with any segment display) is that if a particular segment fails (burns out), an incorrect numeral may be displayed. For instance, if an 8 is selected for display, all filaments must be lit. However, if the G segment of Figure 7 were burned out, a 0 would be displayed instead of an 8.

Fluorescent Segment Displays

The elements of the fluorescent segment display are sealed in a glass envelope like the gas discharge and incandescent displays previously discussed. Figure 10 shows the basic construction of the fluorescent display. The display consists of seven phosphor-coated anodes which are placed on the backing material in the conventional, planar, seven-segment arrangement. A very thin, almost invisible, filament wire is placed between the anodes and the observer.

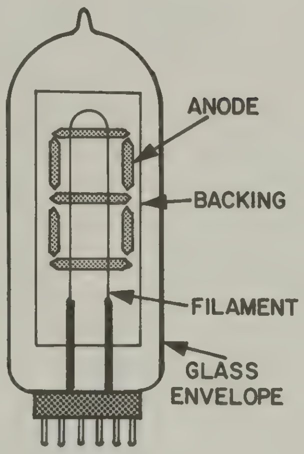


Figure 10

The operation of this display is quite simple. The filament is heated by a supply voltage (generally 1.5V dc) almost to the point of incandescence so that it remains invisible. When a numeral is selected for display, an external circuit switches a positive voltage (12 to 25V dc) to the proper segments, or anodes. Electrons emitted by the heated filament are attracted toward the anodes. As the electrons strike the phosphor covering the anode, it fluoresces or emits light. By applying the proper voltage to various segments, the numerals 0 through 9 can be displayed.

An advantage of this type of display is the natural color of the fluorescent display, a soft bluish green. By using the proper light filters, the display can be filtered to obtain almost any color except deep red. The expected life of a fluorescent display is approximately 20,000 hours, at which time the brightness is about half that of a new display. However, the display may still be readable far beyond this half-bright life figure. One problem with this type of display is that **OPTICAL HOT SPOTS** may be formed on the segments. These are caused by slightly more phosphor being in one area than in another of the segment. Part of a segment then appears brighter than the rest of the segment.

Light-Emitting Diode Displays

A previous lesson described the basic operating characteristics of the light-emitting diode (LED). Gallium arsenide (GaAs) diodes emit near-infrared rays (often called infrared light) and therefore cannot be used for a digital display. For this reason, phosphorus is added to the gallium and arsenide elements to form a gallium arsenide phosphide (GaAsP) display which emits rays in the visible spectrum. A compound of gallium and phosphorus (GaP) also is becoming more widely used as an LED material because of its advantages of efficiency and color variety.

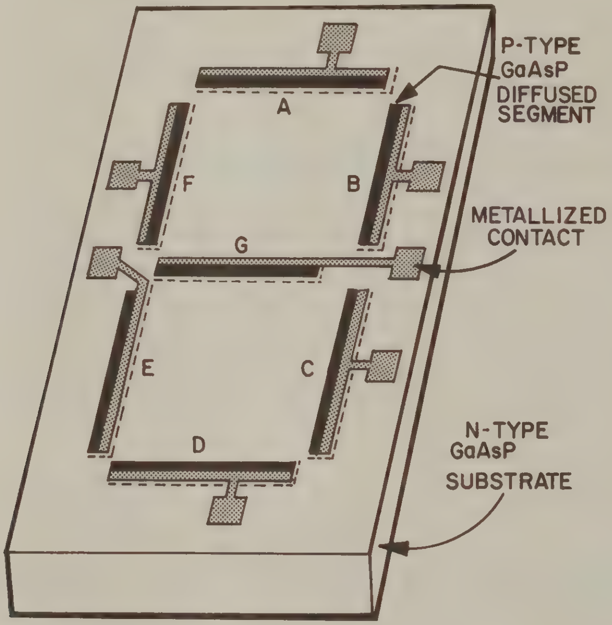


Figure 11

LED displays are planar devices, but they may be constructed in many different configurations and sizes. The most basic form of an integrated circuit, seven-segment LED display is shown in Figure 11. Each segment is a PN diode junction that emits light when forward biased. The N-type material forms the substrate or base material. The P-type material is diffused into the substrate. Each P-type segment has a metalized contact to which external leads are bonded. This configuration, along with the external control circuit for the display, is shown schematically in Figure 12. Switches S_A through S_G provide control for the segments which are to be lit. As shown, S_B and S_C are closed, diode segments B and C are forward biased by battery V_B, and both segments emit light. In Figure 11, when segments B and C emit light, the numeral 1 is displayed. By controlling the amount of forward current (I_F), the amount of light emitted by a segment may be effectively controlled.

The following Practice Exercise questions cover the subjects which you have just studied. They are:

MECHANICAL DISPLAYS

LIGHT TRANSFER DISPLAYS

LIGHT-EMITTING DISPLAYS

GAS DISCHARGE DISPLAYS

INCANDESCENT SEGMENT DISPLAYS

1. An extremely accurate indication of a measurement is characteristic of a (a) digital display, (b) analog meter.

2. In addition to accuracy of the measurement, what other advantage does the digital multimeter of Figure 1A offer?

3. What are the four classes of display devices?

4. When the units display of Figure 2 indicates the numeral 9, what happens when the next index of the units display occurs?

5. What function does the character mask of Figure 3 serve?

6. The projection readout device can only display numerals or letters. True or False?

7. A disadvantage of the rear projection readout is that it has a very limited viewing distance. True or False?

8. Name three light-emitting substances.

9. The Nixie tube has ten cathodes, each formed in the shape of a numeral, which are placed behind one another, and is therefore called a ________ __________.

10. The fine wire mesh located between the cathodes and the observer is part of the Nixie tube's __________.

11. For the cold cathode display of Figure 6, the current through R_L is also through the proper cathode. This current then heats the cathode to produce light and display the numeral. True or False?

12. What color of light is emitted by the Nixie tube?

13. A disadvantage of the gas discharge display is the high voltage required for its operation. True or False?

14. The seven filaments of the incandescent display of Figure 7 are called ______________ ____________________.

15. To display a numeral, the incandescent readout uses what principle of emitting light?

16. There is a possibility of an incorrect display with any seven-segment readout device if one of the segments malfunctions. True or False?

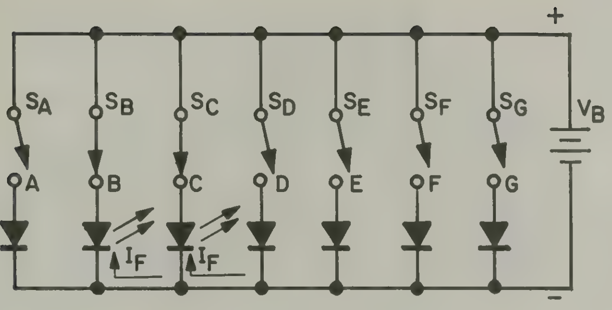


Figure 12

The color of the light emitted by the LED display is controlled by the amounts of gallium, arsenic and phosphorus used. To produce a red, orange, amber or yellow light requires a different combination of the diode materials. Most commonly available displays emit red light because one readily available GaAsP mixture operates most efficiently (greatest light intensity output for a given forward current) in this region of the visible spectrum. Recently, researchers found that a gallium phosphide (GaP) compound could be processed into an LED that emits green light. Green is not the only color of light this combination can produce. By varying the amount of phosphorus in the compound, LED's that emit yellow light or red light can be produced.

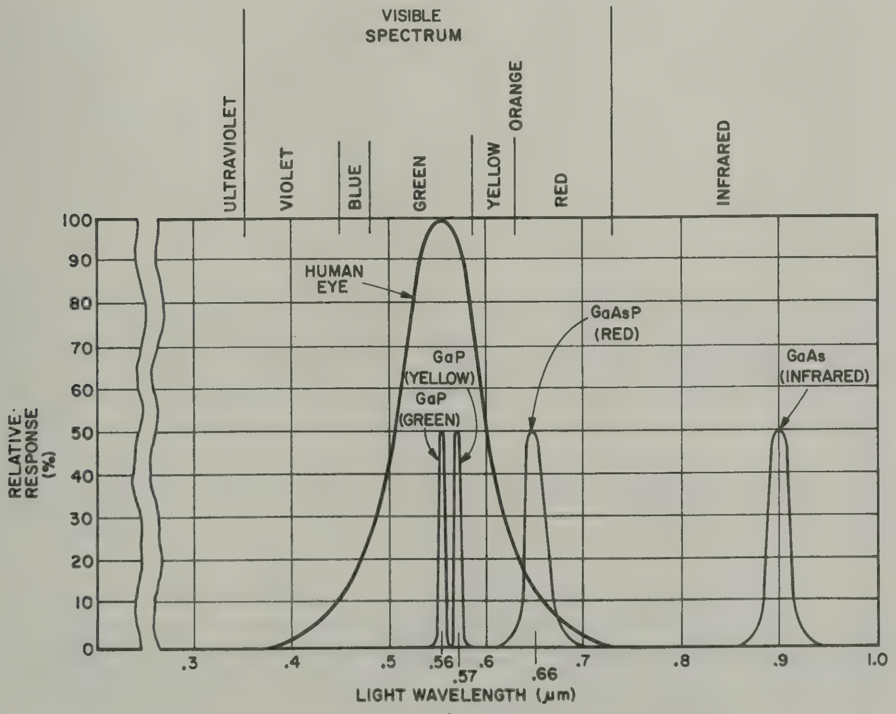
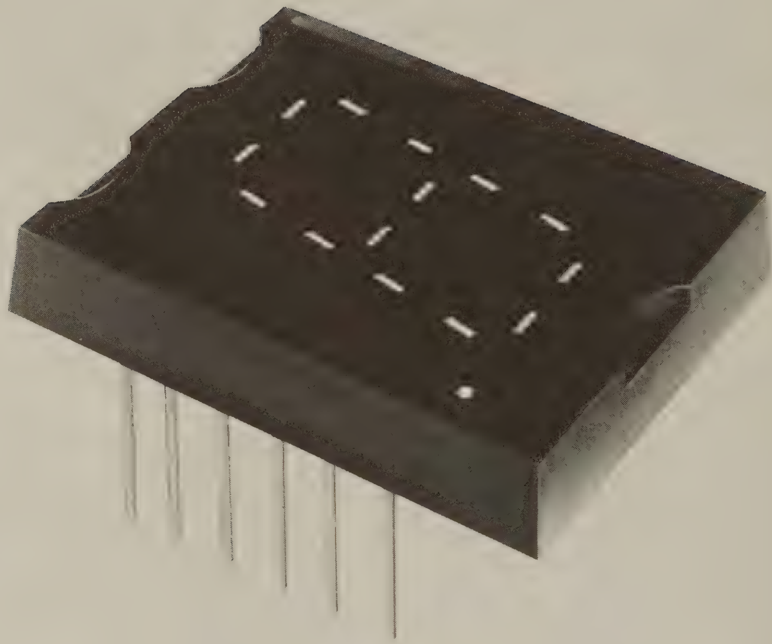


Figure 13



Most electronic displays have an extra element, in this case an LED, to light the decimal point.

Courtesy Litronix, Inc.

Figure 13 shows the light spectrum in which is plotted the response curve for the human eye and the characteristic emission curves of various types of LED's. The end of one color and the beginning of the next color in the visible portions of the light spectrum are not clearly defined lines as the graph shows. Rather, they are regions where the colors overlap and mix, such as between yellow and red where amber and orange appear.

The peak response of the human eye to light is at a wavelength of .56 μm (.56 × 10^{-6} meters). (A μm is a unit of measure, called a micrometer, for the wavelength of light.) The .56 μm wavelength is in the green region. The most efficient LED is the GaAsP diode that emits light at a wavelength of .66 μm. However, the response of the human eye to red light is rather poor. Therefore, LED's emitting green light and LED's emitting red light appear to have similar brightness, even though the red-emitting LED is actually emitting more light.

The GaAsP LED exhibits a linear relationship between forward current and light output. However, because the GaP LED saturates quickly and its light output remains constant for increases in forward current, the linear relationship does not hold true for the GaP devices.

LED displays operate at low voltage and so are compatible with modern test equipment. The LED display is not as fragile as most other displays and it operates over a wide temperature range. The LED display is easy to read. Because it is a planar display, the observer does not have to stand directly in front of the display to read it. LED displays are available in a wide variety of sizes, which make them adaptable to many applications.

LIQUID CRYSTAL DISPLAYS

The liquid crystal display (LCD) is unique because it does not emit or project light for the display of a numeral. The LCD is a dynamic light scattering device requiring an external light source for its reflective and transmissive modes of operation. In the reflective mode, the LCD reflects ambient light (the external light source) in the form of the numeral being displayed. To operate the LCD in the transmissive mode, a lamp is mounted behind the display and its light is transmitted through the display in the form of the numeral.

The operation of the dynamic scattering LCD will be easier to understand after examining its construction, as shown in Figure 14. The backplate of the device, as shown in Figure 14A, supports a transparent electrode. A material which serves as a spacer between the backplate and the faceplate is also placed on the backplate. Seven electrodes are placed on the transparent glass faceplate of Figure 14B in the now familiar seven-segment arrangement. Each electrode is transparent so that ambient light passes through it when the LCD is not displaying a numeral. Figure 14C shows the side view of the assembled, seven-segment liquid crystal display. For a reflective mode LCD only, the backplate is coated with a black substance which absorbs light. Figure 14C also shows that the backplate and the faceplate are sealed by the spacer. Although it serves as a seal when the display is assembled, this spacer provides an area between the two plates for the liquid crystal material. The liquid crystal material which is placed between the backplate and faceplate is transparent to allow ambient light traveling through the faceplate to strike the backplate where it is absorbed by the black coating. With no excitation applied to the electrodes, the display will appear to be black.

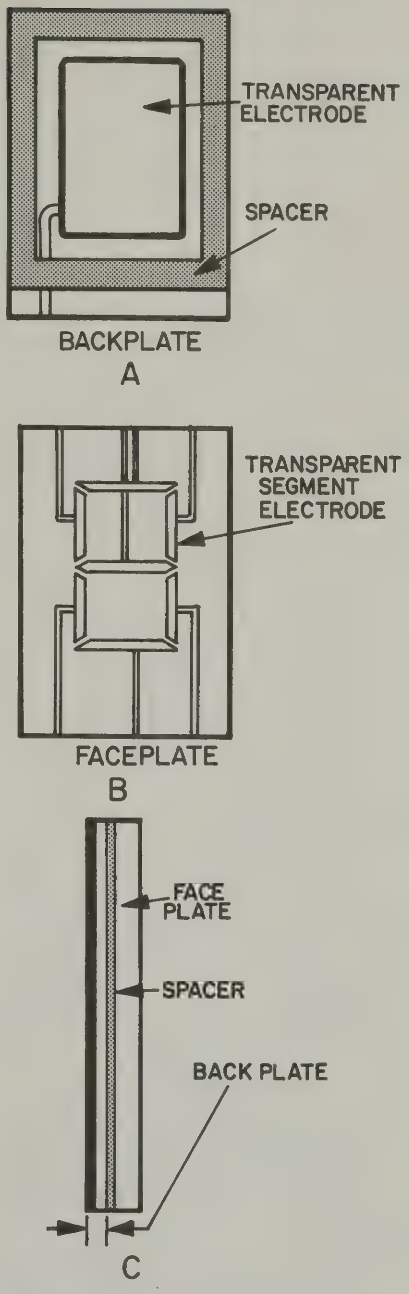


Figure 14

To display a numeral, an excitation signal is applied to the backplate electrode and the proper segment electrodes to create an electric field. Because dc reduces the life expectancy of the display, the excitation signal is usually ac on the order of 1 to 15 volts. When an electric field is created, the molecules of the liquid crystal which are in the electric field become turbulent and reflect the ambient light. All unactivated segments or areas appear black, while all activated segments scatter the light toward the viewer (as a mirror would) and these segments appear to be brightly lit.

Because the light source for the reflective mode is ambient light, the only power used by this display is that required to develop the electric field between the electrodes, which causes the turbulence of the liquid crystal molecules. The current used by the display is approximately 1 $\mu A/cm^2$ of activated area of the LCD. Typically, a display would require 1 to 3 microwatts of power per digit, as compared with tens or hundreds of milliwatts required by other displays.

This extremely low power consumption of the dynamic scattering LCD is a major advantage that makes it the only display capable of performing well under severe power restrictions. One application of the LCD (reflective mode) where the power restrictions are severe is in digital wrist watches which may operate for a year or more without a battery change. Another advantage of the dynamic scattering LCD is that, as the ambient light level increases, the brightness and contrast (readability) of the display also increases. All other electronic displays are less readable at higher ambient light levels. The long life and relatively low cost of the LCD display are also important advantages.

A major disadvantage of this display is that, at extremely low ambient light levels, the display is almost unreadable. Also, the temperature range over which the display operates efficiently is less than most other electronic displays.

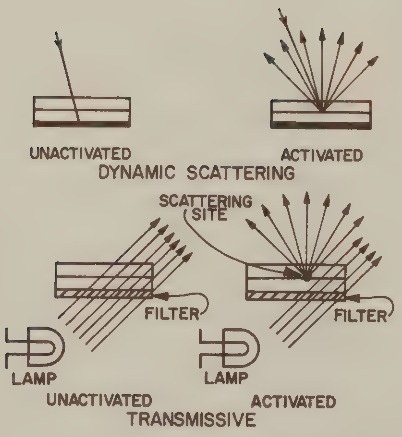


Figure 15

Figure 15 shows some of the differences between the reflective mode of LCD operation and the transmissive mode. To operate the dynamic scattering LCD in the transmissive mode, a lamp is placed behind the display for use as the light source. Its light passes through the filter on the transparent backplate of the display. This filter is a light-directing film which acts like a venetian blind, allowing light to pass through it in only one direction. Therefore, when the display is in the unactivated state (no electric field between its electrodes), it will appear to be dark.

When an electric field activates a portion of the liquid crystal, the light striking that portion of it will be scattered in all directions, as shown in Figure 15. Under this condition, the activated area appears to be brightly lit, while the unactivated areas remain dark. By controlling the segment electrodes which are excited by external circuits, the numerals 0 through 9 may be displayed. Because only a small portion of the light emitted by the lamp is scattered for display, the lamp must have a relatively high power rating (typically, 0.5 watt) as compared to other displays.

The liquid crystal display operates relatively slowly and therefore cannot compete with the LED display for applications requiring high display rates.

A typical display rate of a liquid crystal display is one character change per second. An advantage of operating the LCD in the transmissive mode is that the display does not depend on ambient light conditions. A disadvantage is that additional power is required to operate the lamp.

ALPHANUMERIC DISPLAYS

An alphanumeric display, capable of displaying any letter of the alphabet, as well as any numeral from 0 to 9, is the GaAsP LED display shown in Figure 16. This display consists of 35 LED junctions which are arranged in 7 rows and 5 columns. By applying a forward bias to the proper diodes, any of the alphabetic and numeric characters previously described can be displayed.

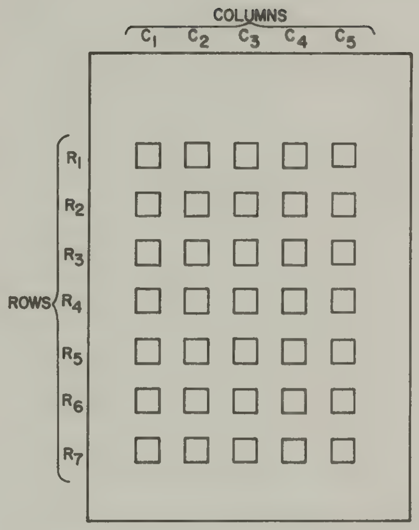


Figure 16

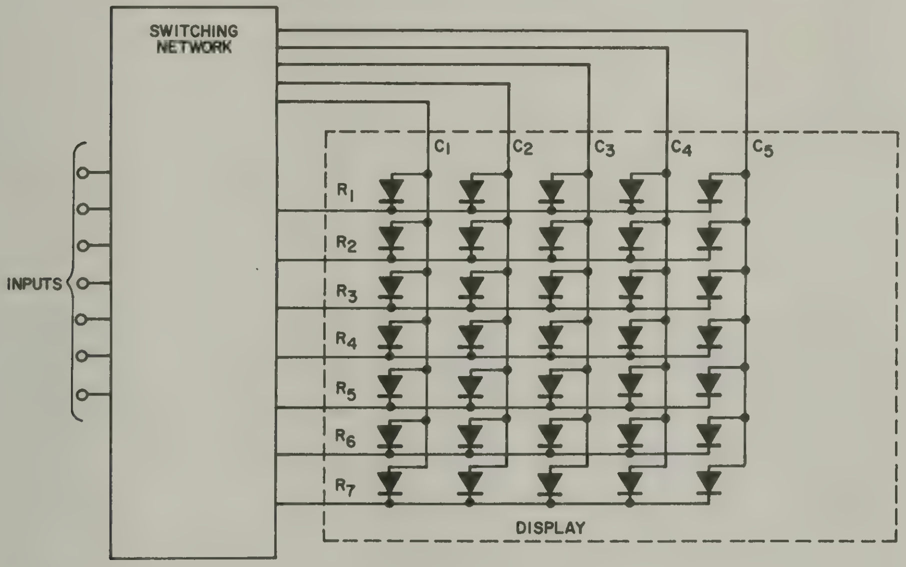
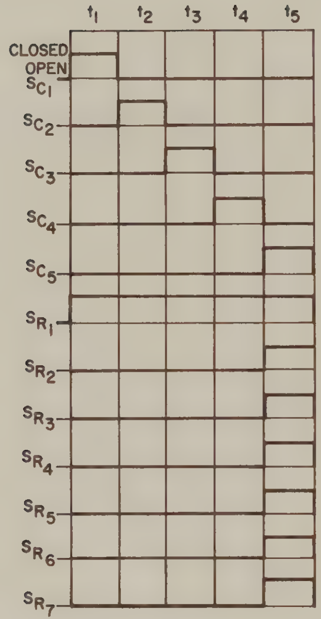
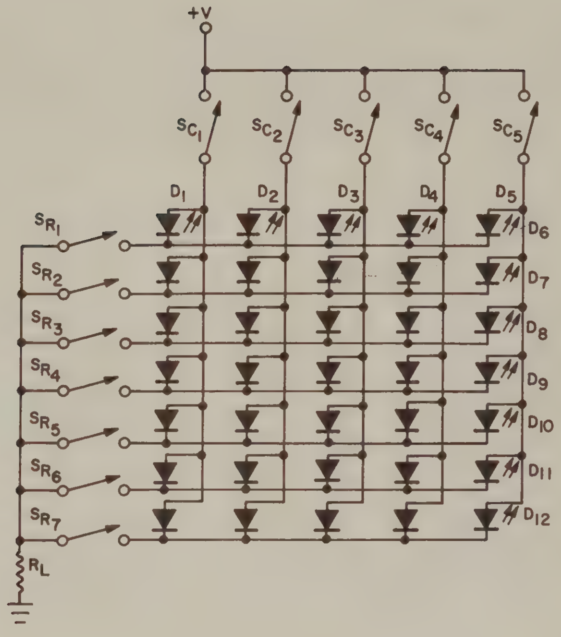


Figure 17

The alphanumeric display is controlled by the complex switching network shown in Figure 17. The operation of this switching network will not be discussed in detail in this lesson. The switching network, however, provides forward bias voltages to the appropriate diodes of the display as determined by its input signal. This is accomplished by a process called **SCANNING.** The scanning process means that the diodes are turned on one column at a time. When a column is scanned, all of the row connections energize the proper diodes in that column. The next column is then scanned, etc., until all five columns have been scanned. After all of the columns have been scanned, the process is repeated.



B

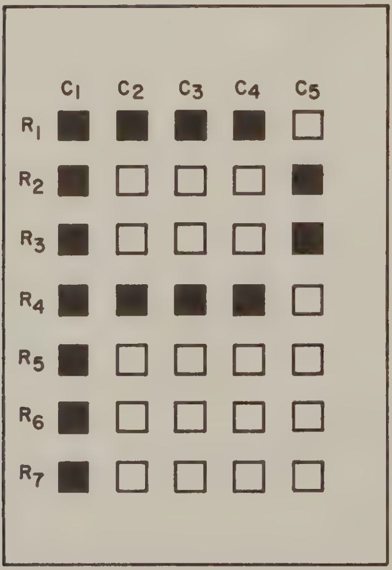


A

Figure 18

As an example of the scanning process, let's assume that the numeral 7 is to be displayed. Figure 18A shows a simplified switching arrangement by which the scanning process can be simulated. Columns C_1 through C_5 (Figure 16) are connected to +V by switches S_{C_1} through S_{C_5} (Figure 18A). Likewise, rows R_1 through R_7 (Figure 16) are connected to ground by R_L and switches S_{R_1} through S_{R_7} (Figure 18A). The switches are all shown in the open position.

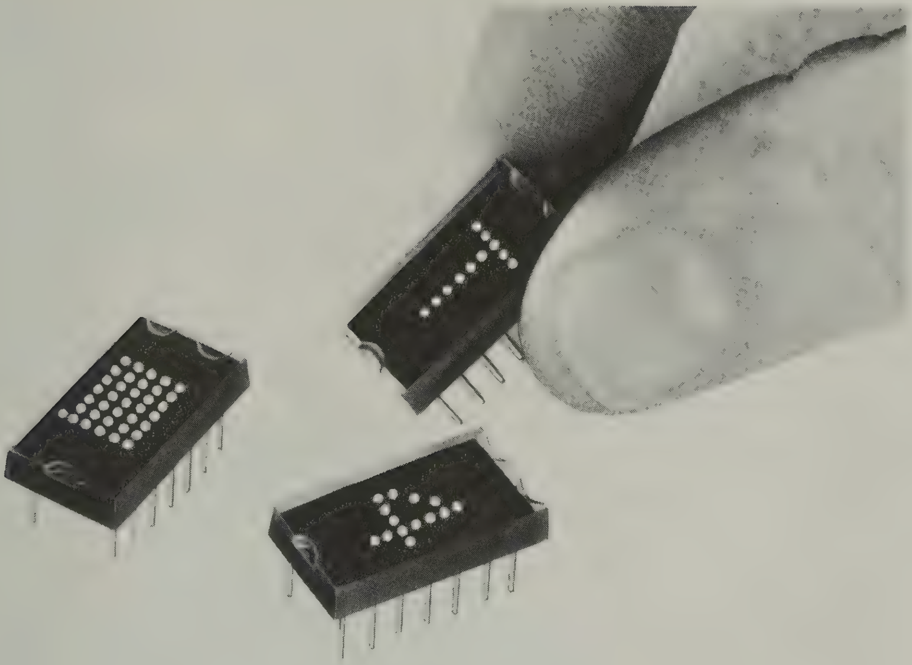
The numeral 7 can be displayed by closing the switches in the sequence shown in the timing diagram of Figure 18B. At time t_1, switches S_{C_1} and S_{R_1} simultaneously close and diode D_1 lights. At time t_2, S_{C_2} and S_{R_1} simultaneously close and D_2 lights. At time t_3, S_{C_3} and S_{R_1} simultaneously close and D_3 lights. At time t_4, S_{C_4} and S_{R_1} simultaneously close and D_4 lights. At time t_5, S_{C_5} and S_{R_1} through S_{R_7} simultaneously close and D_5 through D_{12} light. Each diode will be turned on for 2 milliseconds, for a total display repetition rate of 10 milliseconds. Thus, even though the display is flashing 100 times per second, it appears to have a continuous glow to the human eye.



C

Figure 18

To illustrate the appearance of the letter P, Figure 18C shows the display with the proper diodes lit. These diodes are forward biased by using the scanning method. At time t_1, switch S_{C_1} and all of the row switches simultaneously close to light all of the diodes in the first column. At time t_2,



Diode matrix devices are ideal for alphanumeric displays.
Courtesy Dialight Corporation

S_{C_2}, S_{R_1} and S_{R_4} simultaneously close. At time t_3, S_{C_3}, S_{R_1} and S_{R_4} close. At time t_4, S_{C_4}, S_{R_1} and S_{R_4} close. At time t_5, S_{C_5}, S_{R_2} and S_{R_3} close. By repeating this process 100 times per second, the display appears to be lit continuously.

Some of the alphabetic characters must appear on the display differently than we are accustomed to seeing them in order to avoid ambiguity. For example, the number 8 could be mistaken for the letter B or vice versa. To prevent this, the characters are displayed as shown in the Appendix of this lesson.

The alphanumeric display is also called a dot matrix or diode array display. Multiple-character diode array displays are used to display as many as 700 characters of alphabetic and numeric information. The scanning method is also used with these larger diode arrays to display the information.

CRT DISPLAYS

When it is necessary to display a large amount of information (5000 to 6000 characters), the cathode ray tube (CRT) is used. For example, you may have observed your flight number, departure and arrival times, and boarding information displayed on a TV monitor at the airport. Among other important applications of the CRT are computer output displays.

The size of the CRT could be as small as 3 inches or as large as 16 inches (measured diagonally), depending on the application. Generally speaking, CRT's from 3 to 7 inches operate using electrostatic deflection. CRT's larger than 7 inches use an electromagnetic deflection system.

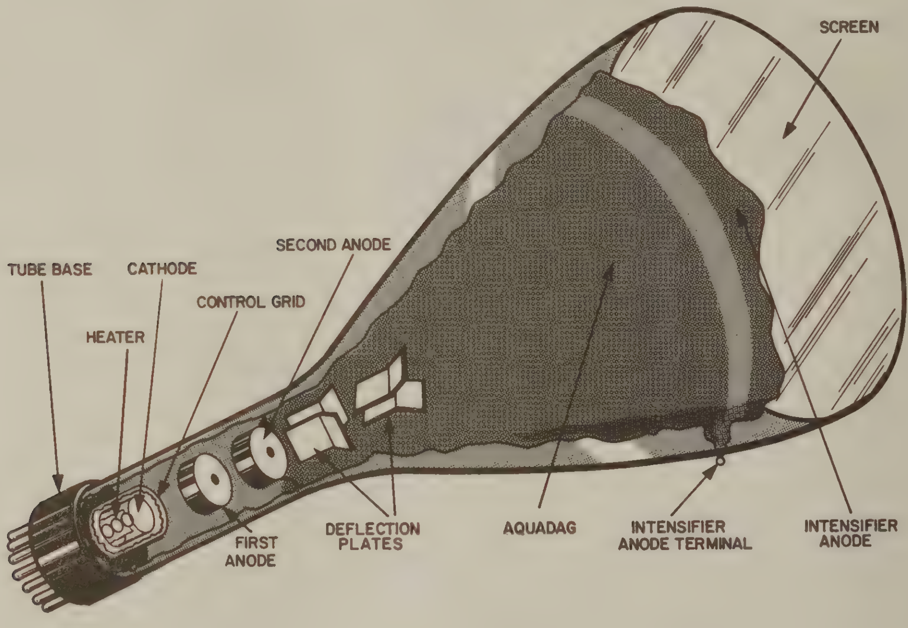


Figure 19

A CRT using electrostatic deflection and focusing is shown in Figure 19. The heated cathode emits electrons when properly biased. These electrons are attracted to the first anode where the electrons are focused into an electron beam. As the electrons in the beam are speeded up by the very high potential on the second anode, the deflection plates deflect the electron beam horizontally and vertically across the screen of the CRT. The intensifier anode speeds up the electrons so that they travel at a very high velocity as they strike the screen and produce light.

CRT's larger than 7 inches use electromagnetic deflection and electrostatic focusing, as shown in Figure 20. Except for the deflection system, the operation of this CRT is the same as described for the CRT of Figure 19. The yoke contains two coils which perform the same function as the deflection plates in the electrostatic system. However, electromagnetic deflection

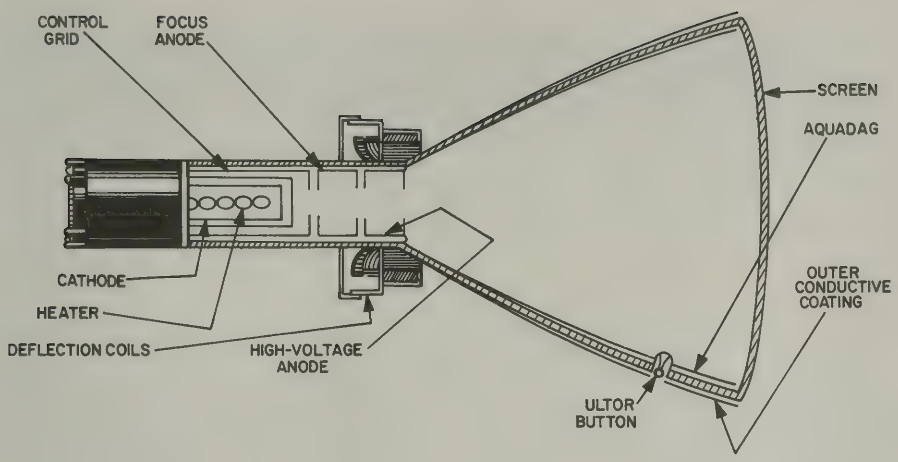


Figure 20

offers an advantage in that the beam can be deflected over a greater screen area and still remain in focus while producing a brighter image.

A CRT which is used to display alphanumeric information is called a CRT readout or a monitor. The information which the monitor receives is the output of a computer or other device which generates a signal representing the characters to be displayed. This signal also contains synchronizing signals which are used to synchronize the horizontal and vertical deflection circuits of the monitor with the incoming character signal.

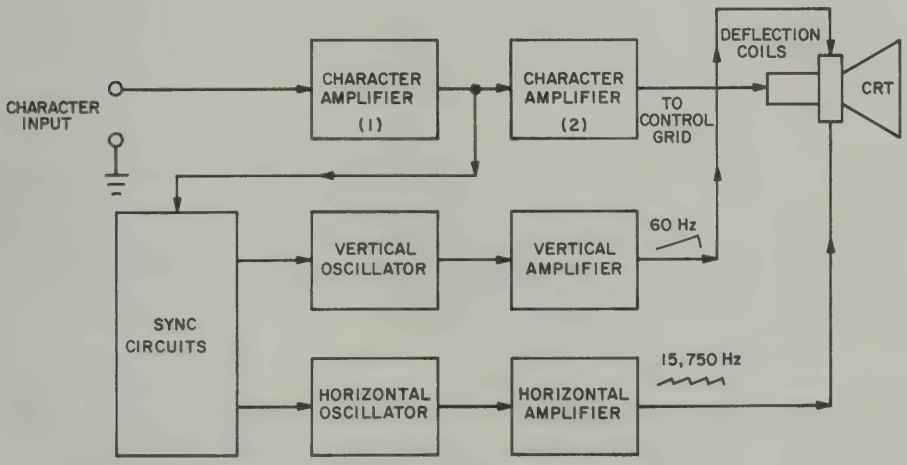
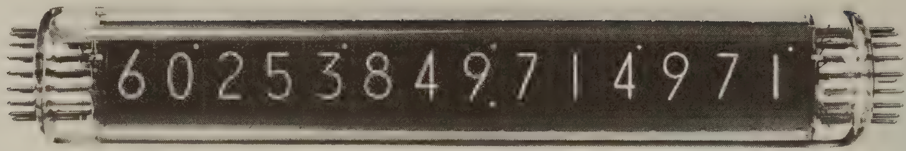


Figure 21



The multiple-digit, cold cathode, gas discharge display reduces the cost per digit and size requirements of the display. Courtesy Amperex Electronic Corp.

The character signal is applied to the character input terminals of the monitor, as shown in the block diagram of Figure 21. The input signal is amplified by two character amplifiers and applied to the control grid of the CRT. A sample of the imput signal is taken from the output of character amplifier (1) and fed to the sync circuits. The sync circuits obtain the vertical and horizontal synchronizing signals from the input signal to trigger the vertical and horizontal oscillators. Each oscillator produces a voltage having a waveform which causes sawtooth current in the output of the following amplifier stage. Thus, the vertical deflection circuit (vertical oscillator and amplifier) supplies a 60-Hz sawtooth of current, and the horizontal deflection circuit (horizontal oscillator and amplifier) supplies a 15,750-Hz sawtooth of current to their respective deflection coils or plates.

1/2
62/5
1/3 6/15

As shown in Figure 21, the 60-Hz sawtooth current waveform passes through the vertical deflection coils, and the horizontal deflection coils carry the 15,750-Hz sawtooth current waveform. These currents produce magnetic fields which deflect the electron beam. The 60-Hz sawtooth waveform indicates the gradual rise and rapid fall of the vertical deflection current. During the long gradual rise, the electron beam moves from the top to the bottom of the CRT. The beam returns very quickly to the top of the screen during the sharp fall of current in the deflection coils.

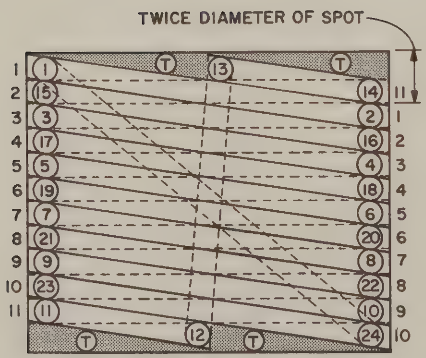


Figure 22

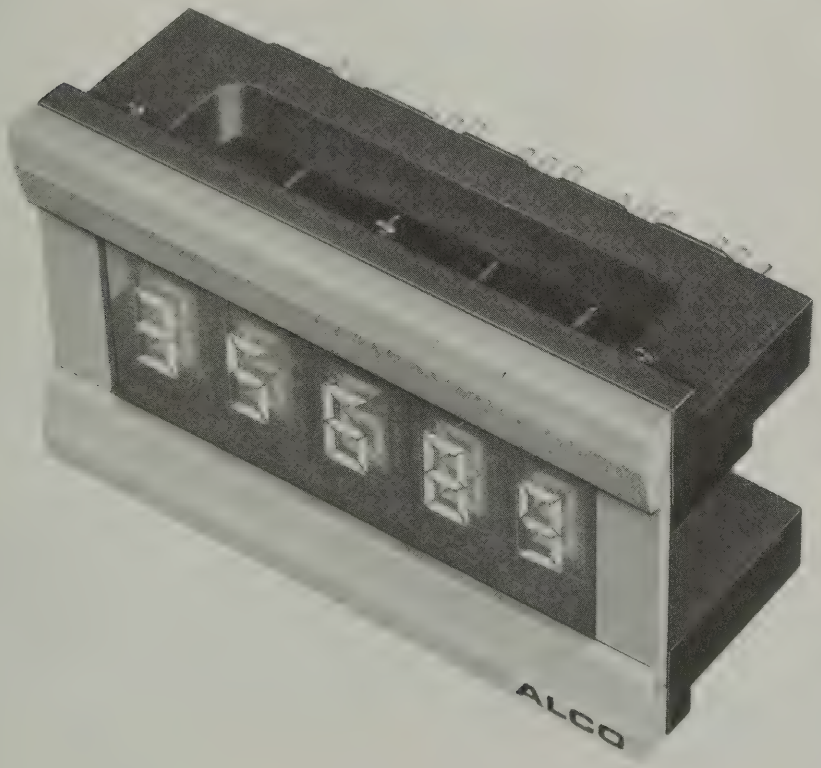
Several cycles of horizontal sawtooth current are represented by the 15,750-Hz waveform. During each cycle, the beam moves from left-to-right to trace a line during each gradual rise of current. The beam returns quickly to the left side of the screen when the current falls sharply in the horizontal deflection coils.

The vertical and horizontal sawtooth currents are synchronized with the incoming character signals which are applied to the control grid of the CRT. In this manner, the phosphor-coated CRT screen is scanned to produce a display of the character information. This scanning procedure is shown in the simplified sketch of Figure 22.

In Figure 22, the spot is shown having a greatly exaggerated diameter. The various positions of the spot are indicated by the circles such as those marked 1, 15, 3, etc., at the left edge and those marked 4, 16, 2, etc., at the right edge of the screen. In addition, the 11 scanning lines are numbered from the top to the bottom of the screen on the outside edges. The shaded T areas are the small parts of the screen not covered by the electron beam (scanning spot).

Starting at position (1) in the upper left-hand corner, the scanning spot moves to position (2), tracing out the top scanning line number 1. During this left-to-right movement, the spot also travels downward for a distance equal to twice its diameter. Consequently, after retracing rapidly from position (2) to position (3), it is ready to trace scanning line number 3, to position (4), having skipped line number 2. After moving to position (5), it scans lines 5, 7, 9 and the first half of 11 in order, having skipped lines 4, 6, 8 and 10.

At the middle of line 11, which is position (12), the beam has reached the end of vertical deflection and is suddenly vertically retraced to position (13) at



Unlike most display devices, the liquid crystal is more readable in bright ambient light conditions.
Courtesy Alco Electronic Products, Inc.

This CRT readout and keyboard is one way in which man and computer may communicate. The monitor is used when many digits of information must be displayed.
Courtesy RCA Corporation

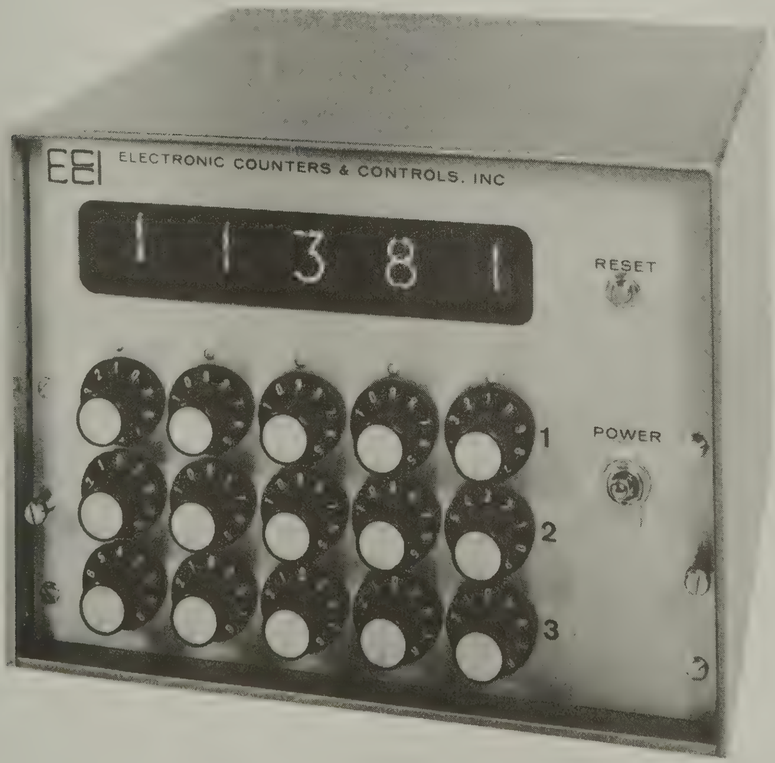
the top, where it completes the tracing of the eleventh scanning line. From position (13) to position (14), because the spot moves only halfway across the screen, it travels downward a distance equal only to its diameter. Therefore, retracing to the left side of the screen, it arrives at position (15) to begin scanning line number 2, which is in between the lines scanned previously.

From position (15) to position (16), the spot traces line number 2 and again moves downward a distance equal to twice its diameter, so that retracing to position (17), it is ready to scan line 4. Similarly, lines 6, 8 and 10 are scanned, with lines 3, 5, 7 and 9 being skipped. Reaching the end of line 10 at position (24), the beam is again at the end of vertical deflection and so retraces to position (1) in the upper left-hand corner of the screen, ready to begin line 1 again.

Thus, in this scanning arrangement, in order to trace out all of the lines one time, the beam spot completes 2 vertical cycles of deflection. This is called interlace scanning, and the screen of the CRT is actually traced $262^{1}/_{2}$ times horizontally for each vertical scan period, called a field. Thus, it takes 2 fields to completely scan all the horizontal lines for a complete frame of 525 scan lines.

With this method of interlace scanning, as one set of lines of a field begins to diminish slightly in intensity, the second field is being traced at maximum brilliance. This averages into an evenly illuminated field and almost no flicker is noticed. Incidentally, this is the same process used by the television receiver in your home.

The character signal applied to the control grid determines when the electron beam is emitted from the cathode of the CRT. The deflection system determines where that beam strikes the face of the CRT to produce light. In this manner, a series of dots is traced horizontally on each line to form alphanumeric characters on the face of the CRT. This is similar to the 5 × 7 LED array previously discussed. In fact, each character of the display is formed in a 5 × 7 dot matrix on most CRT displays.



The multiplanar, gas discharge displays are used in many industrial control instruments because of the reliability of the display.

Courtesy Electronic Counters and Controls, Inc.

63
14
252
63
882

As a practical example, a 9-inch (measured diagonally) picture tube is capable of displaying 14 lines of characters in the vertical direction (top to bottom), leaving a space equal in height to one line between each line. In the horizontal direction, this CRT is capable of displaying 63 characters per line. Therefore, the 9-inch CRT readout is capable of displaying 882 alphanumeric characters in 14 lines or sentences.

In addition to the display of alphanumeric characters, the CRT readout is capable of displaying charts and graphs. For graphic displays, color picture tubes may be used to show several curves on the same graph. This readout device is the most flexible, in terms of application, of all the displays available today. This display device is reliable and relatively inexpensive when considering cost versus number of digits displayed.

SUMMARY

There are many types of electronic display devices in use today and each is designed for a specific application. The considerations for each type of display are ambient light conditions, power consumption, reliability, readability, cost, size, and complexity of external circuits required to operate the display. Each of the displays discussed in this lesson ~~is in use in industry;~~ therefore, the operation and terminology of each type should be thoroughly understood.

The following Practice Exercise questions cover the subjects which you have just studied. They are:

LIGHT-EMITTING DISPLAYS

FLUORESCENT SEGMENT DISPLAYS

LIGHT-EMITTING DIODE DISPLAYS

LIQUID CRYSTAL DISPLAYS

ALPHANUMERIC DISPLAYS

CRT DISPLAYS

17. Which element of a fluorescent display emits light?

18. When forward biased, the GaAs diode emits ____________ __________ light rays.

19. Can a seven-segment LED have more than one diode junction per segment?

20. What are the four colors which a GaAsP display may emit?

21. What colors of light can be displayed by a GaP display?

22. At what color of light in the visible spectrum is the response of the human eye greatest?

23. Controlling the forward current through the diode junction controls the light output for either a GaAsP or a GaP device. True or False?

24. Is the multiple-digit LED device a planar display?

25. A liquid crystal display emits either red or green light. True or False?

26. The electrodes of an LC display are transparent. True or False?

27. The liquid crystal is transparent until it is acted upon by an electric field. True or False?

28. The power requirement of the LCD is (a) high, (b) low, (c) extremely low.

29. In the reflective mode, the liquid crystal display operates most efficiently in the dark. True or False?

30. Even though the LCD requires very little power, it has an extremely low display rate. True or False?

31. Alphanumeric characters are displayed on a diode matrix display using an external switching circuit which operates by the ______________ principle.

32. In Figure 16, if the numeral 8 is displayed, and column C_1 is being scanned, which of the rows are also being scanned?

33. Even though the scanning process causes a display to flash at the rate of 100 times per second, the human eye cannot detect flashes at this rate and it appears to be continuously lit. True or False?

34. An 11-inch CRT readout uses ______________ deflection and ______________ focusing.

35. The vertical deflection signal is a __________ Hz __________ of current.

36. The horizontal deflection signal is a __________ Hz __________ of current.

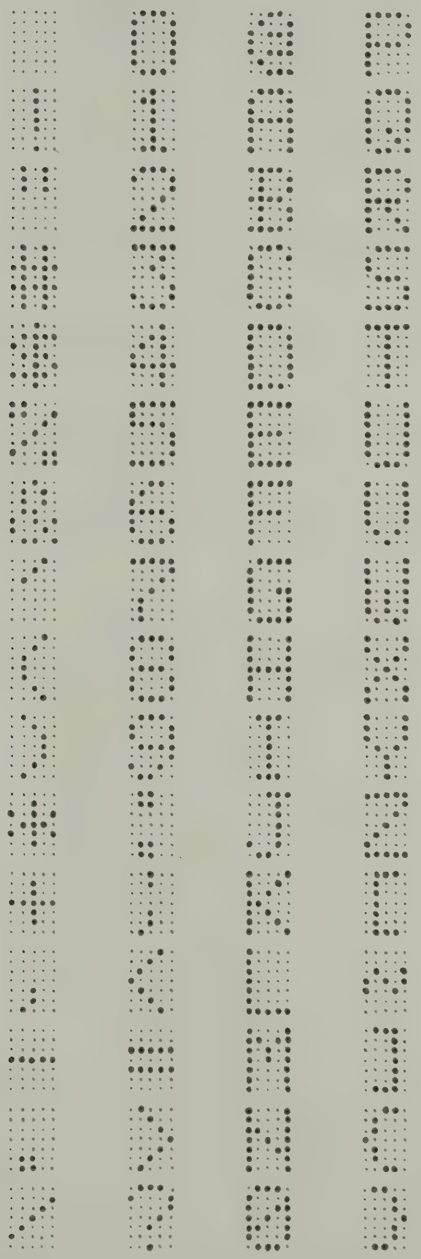
37. With the interlace scanning method, each time the beam spot traces a horizontal line it has moved downward a distance equal to what?

38. While the horizontal and vertical deflection systems are deflecting the beam spot to produce interlace scanning, how are the alphanumeric characters formed on the screen?

39. The interlace scanning method produces a frame which is repeated 30 times per second. True or False?

APPENDIX
ALPHANUMERIC CHARACTERS

The following figure shows the appearance of the alphanumeric characters as they appear in a 5 × 7 matrix or diode array.



IMPORTANT DEFINITIONS

INCANDESCENCE—The emission of visible light from a material caused by heating that material until it glows.

IONIZATION—The process where a gas atom is broken into two parts; a free electron and positively charged ion. This process causes a "breakdown" of the insulating characteristics of the gas, causing a gas-filled tube to be more conductive than a vacuum tube.

MULTIPLANAR DEVICE—A device containing more than one element, with each element in a different vertical or horizontal plane.

OPTICAL HOT SPOTS—An electronic display impurity in which a portion of the display is noticeably brighter than the rest of the display.

PLANAR—A display in which all elements of the display are in a single plane, or flat surface.

SCANNING—A display process in which the field of view is not simultaneously illuminated, but the tiny display elements are illuminated, line by line, at a rapid rate to form an image. The scanning rate is so rapid that the field of view appears to be illuminated continuously.

PRACTICE EXERCISE SOLUTIONS

1. (a) digital display.

2. Accuracy of the reading.

3. Mechanical, light transfer, light emitting, CRT.

4. The index teeth engage with the index gear and, as the units display rotates, the numeral 0 will appear on it while the tens display is advanced one digit.

5. It passes light in the image of a numeral to be displayed on the screen.

6. False—In addition, it can display a word or a message.

7. False—Depending upon the type of lamps that are used, it can be seen at viewing distances as great as 100 feet.

8. The metal used as the filament of an incandescent lamp, GaAsP and GaP compounds and gases such as neon.

9. multiplanar display

10. anode

11. False—Since it is a cold cathode display, the cathode does not get hot. However, the current through the cathode ionizes the neon to display the numeral.

12. Orange-red.

13. True

14. display segments

15. Heating the proper filaments to the point of incandescence.

16. True

17. The phosphor-coated anode.

18. near infrared

19. Yes

20. Red, orange, amber or yellow.

21. Green, yellow, or red.

DE VRY INSTITUTE OF TECHNOLOGY
4141 BELMONT AVENUE, CHICAGO, ILLINOIS 60641

ONE OF THE
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7430A
EXAMINATION CHECK SHEET

1. D - THE GAS DISCHARGE DISPLAY OPERATES ON THE PRINCIPLE OF -- IONIZATION.
In a gas discharge display, the anode is connected to a high positive potential. When cathode current is present, an electric field is created and the neon closest to the cathode is ionized, producing the display.

2. B - A DISPLAY WHICH GENERATES R-F NOISE AND CANNOT BE USED IN SENSITIVE RECEIVERS WITHOUT SPECIAL SHIELDING IS -- A GAS DISCHARGE.
The ionization of the neon produces r-f noise which will cause interference with reception unless proper shielding is provided.

3. A - IN FIGURE 7, WHICH SEGMENTS MUST BE LIT IN ORDER FOR THE NUMERAL SIX TO BE DISPLAYED? -- A, F, E, D, C AND G.
This is the only combination which displays the numeral 6 according to Figure 8 of this lesson.

4. D - A GaAsP MIXTURE CAUSES A DISPLAY TO EMIT RED LIGHT. A DISPLAY CAN EMIT GREEN LIGHT BY USING A MIXTURE OF -- GALLIUM AND PHOSPHORUS (GaP).
This produces a GaP display which emits light at .56μm in the green region of the light spectrum.

5. A - THE ONLY DISPLAY WHOSE EFFICIENCY INCREASES AS AMBIENT LIGHT INCREASES IS THE -- LIQUID CRYSTAL OPERATED IN THE REFLECTIVE MODE.
The LCD depends upon ambient light for its display. As the ambient light increases, the display brightness and contrast increases.

6. D - IN FIGURE 16 AND THE APPENDIX OF THIS LESSON, WHEN THE NUMERAL 8 IS DISPLAYED AND COLUMN C_3 IS BEING SCANNED, WHICH OF THE ROW DIODES WILL BE FORWARD BIASED? -- R_1, R_4 AND R_7.
From the Appendix, when column C_3 is scanned, the top, middle, and the bottom diodes are on. These diodes correspond to rows R_1, R_4 and R_7.

7. C - A FOUR-INCH CRT WOULD USE -- ELECTROSTATIC DEFLECTION AND ELECTROSTATIC FOCUSING.
CRT's which are smaller than seven inches use this type of deflection and focus arrangement. CRT's larger than seven inches use the electromagnetic deflection and electrostatic focus arrangement.

8. C - DURING THE LONG GRADUAL RISE IN THE HORIZONTAL SAWTOOTH DEFLECTION CURRENT FOR A CRT DISPLAY, THE BEAM IS DEFLECTED FROM -- LEFT TO RIGHT.
A rise in the horizontal sawtooth current deflects the beam from left to right and the rapid fall returns the beam to the left side of the CRT.

9. C - DURING THE RAPID FALL OF THE VERTICAL SAWTOOTH CURRENT, THE BEAM MOVES FROM -- BOTTOM TO TOP.
A rise in the vertical sawtooth current deflects the beam from top to bottom and the rapid fall of the current returns the beam to the top of the CRT.

10. D - THE INTERLACE SCANNING METHOD PRODUCES A FRAME WHICH -- CONSISTS OF 525 HORIZONTAL LINES.
A field, consisting of 262 1/2 horizontal lines, is repeated 60 times per second. Two fields produce an interlaced frame consisting of 525 lines that is repeated 30 times per second.

QUESTIONS

IMPORTANT—These instructions **MUST** be accurately followed to avoid loss, or errors in grading.

Indicate your answer on this sheet by filling in the box for the most correct answer to each question, as illustrated in the example below.

When all questions have been answered, place the answer card in the proper position to line up the boxes on the card with the boxes on the sheet.

Next, copy the complete lesson code into the space provided on the card, and fill in the answer boxes to correspond with those previously filled in on this sheet.

Before mailing, be certain your correct student number, name and address appear on the card.

LESSON CODE
7430A

Example: A ■ B ☐ C ☐ D ☐ Perhaps the earliest rail car to combine a gasoline engine driving an electric generator was demonstrated in the Chicago area in
(A) 1890. (B) 1910. (C) 1920. (D) 1930.

1. A ☐ B ☐ C ☐ D ☒ **The gas discharge display operates on the principle of**
(A) fluorescence. (B) incandescence. (C) reflection. (D) ionization.

2. A ☐ B ☒ C ☐ D ☐ **A display which generates r-f noise and cannot be used in sensitive receivers without special shielding is**
(A) an LED. (B) a gas discharge. (C) an incandescent. (D) a liquid crystal.

3. A ☒ B ☐ C ☐ D ☐ **In Figure 7, which segments must be lit in order for the numeral 6 to be displayed?**
(A) A, F, E, D, C and G. (B) F, E, D, C, B and G. (C) F, E, D and C. (D) A, F, E, D and C.

4. A ☐ B ☐ C ☐ D ☒ **A GaAsP mixture causes a display to emit red light. A display can emit green light by using a mixture of**
(A) GaAsP and increasing its phosphorus content. (B) GaAsP and decreasing its phosphorus content. (C) GaAsP and increasing its arsenic content. (D) gallium and phosphorus (GaP).

5. A ☒ B ☐ C ☐ D ☐ **The only display whose efficiency increases as ambient light increases is the**
(A) liquid crystal operated in the reflective mode. (B) liquid crystal operated in the transmissive mode. (C) GaAsP LED. (D) GaP LED.

6. A ☐ B ☐ C ☐ D ☒ **In Figure 16 and the Appendix of this lesson, when the numeral 8 is displayed and column C_3 is being scanned, which of the row diodes will be forward biased?**
(A) R_1, R_4 and R_6. (B) R_1, R_2 and R_5. (C) R_1, R_3 and R_6. (D) R_1, R_4 and R_7.

7. A ☐ B ☐ C ☒ D ☐ **A 4-inch CRT would use**
(A) electromagnetic deflection and electrostatic focusing. (B) electromagnetic deflection and electromagnetic focusing. (C) electrostatic deflection and electrostatic focusing. (D) electrostatic deflection and electromagnetic focusing.

8. A ☐ B ☐ C ☒ D ☐ **During the long gradual rise in the horizontal sawtooth deflection current for a CRT display, the beam is deflected from**
(A) top to bottom. (B) right to left. (C) left to right. (D) bottom to top.

9. A ☐ B ☐ C ☒ D ☐ **During the rapid fall of the vertical sawtooth current, the beam moves from**
(A) top to bottom. (B) left to right. (C) bottom to top. (D) right to left.

10. A ☐ B ☐ C ☐ D ☒ **The interlace scanning method produces a frame which**
(A) consists of 262½ horizontal lines. (B) is repeated 60 times per second. (C) is repeated 15,750 times per second. (D) consists of 525 horizontal lines.

PRACTICE EXERCISE SOLUTIONS (Continued)

22. Green, which has a wavelength of .56 μm.

23. False—The GaP device saturates quickly. Therefore, the linear relationship between forward current and light output does not apply.

24. Yes—Any seven-segment LED or diode matrix display is a planar display.

25. False—A liquid crystal display either reflects or transmits light; it never emits light of any color.

26. True

27. True

28. (c) extremely low.

29. False—In the dark, the LCD cannot be seen because there is no ambient light to reflect.

30. True

31. scanning

32. R_2, R_3, R_5, and R_6.

33. True

34. electromagnetic; electrostatic

35. 60; sawtooth

36. 15,750; sawtooth

37. Twice the diameter of the spot.

38. The character signal is applied to the control grid of the picture tube and controls the intensity of the beam spot. Therefore, the beam is emitted from the cathode at the proper times during deflection to produce dots, which form the characters.

39. True

QUESTIONS

IMPORTANT—These instructions **MUST** be accurately followed to avoid loss, or errors in grading.

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7430A

Example: Perhaps the earliest rail car to combine a gasoline engine driving an electric generator was demonstrated in the Chicago area in

A ■ B ☐ C ☐ D ☐

(A) 1890. (B) 1910. (C) 1920. (D) 1930.

1. A ☐ B ☐ C ☐ D ☒

The gas discharge display operates on the principle of
(A) fluorescence. (B) incandescence. (C) reflection. (D) ionization.

2. A ☐ B ☒ C ☐ D ☐

A display which generates r-f noise and cannot be used in sensitive receivers without special shielding is
(A) an LED. (B) a gas discharge. (C) an incandescent. (D) a liquid crystal.

3. A ☒ B ☐ C ☐ D ☐

In Figure 7, which segments must be lit in order for the numeral 6 to be displayed?
(A) A, F, E, D, C and G. (B) F, E, D, C, B and G. (C) F, E, D and C. (D) A, F, E, D and C.

4. A ☐ B ☐ C ☐ D ☒

A GaAsP mixture causes a display to emit red light. A display can emit green light by using a mixture of
(A) GaAsP and increasing its phosphorus content. (B) GaAsP and decreasing its phosphorus content. (C) GaAsP and increasing its arsenic content. (D) gallium and phosphorus (GaP).

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The only display whose efficiency increases as ambient light increases is the
(A) liquid crystal operated in the reflective mode. (B) liquid crystal operated in the transmissive mode. (C) GaAsP LED. (D) GaP LED.

6. A ☐ B ☐ C ☐ D ☒

In Figure 16 and the Appendix of this lesson, when the numeral 8 is displayed and column C_3 is being scanned, which of the row diodes will be forward biased?
(A) R_1, R_4 and R_6. (B) R_1, R_2 and R_5. (C) R_1, R_3 and R_6. (D) R_1, R_4 and R_7.

7. A ☐ B ☐ C ☒ D ☐

A 4-inch CRT would use
(A) electromagnetic deflection and electrostatic focusing. (B) electromagnetic deflection and electromagnetic focusing. (C) electrostatic deflection and electrostatic focusing. (D) electrostatic deflection and electromagnetic focusing.

8. A ☐ B ☐ C ☒ D ☐

During the long gradual rise in the horizontal sawtooth deflection current for a CRT display, the beam is deflected from
(A) top to bottom. (B) right to left. (C) left to right. (D) bottom to top.

9. A ☐ B ☐ C ☒ D ☐

During the rapid fall of the vertical sawtooth current, the beam moves from
(A) top to bottom. (B) left to right. (C) bottom to top. (D) right to left.

10. A ☐ B ☐ C ☐ D ☒

The interlace scanning method produces a frame which
(A) consists of 262½ horizontal lines. (B) is repeated 60 times per second. (C) is repeated 15,750 times per second. (D) consists of 525 horizontal lines.

MOTORS AND GENERATORS

7435

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Each of the two 3600 HP diesel-electric road switches shown above has a 20 cylinder engine, one traction alternator and six dc traction motors. Each diesel-electric road switcher has a continuous tractive effort of 83,000 pounds. AC and dc motors and generators of various ratings are key elements in the operation of these locomotives.

Courtesy Electro-Motive Division of General Motors

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Learn from the mistakes of others—
you can't live long enough to make
them all yourself.
—Martin Vanbee

MOTORS AND GENERATORS

Imagine yourself walking through a large, modern factory. Here, motors and generators are used to power the giant machines that punch, drill, cut and assemble materials into useful products. Skilled technicians watch over the machines and their electronic controls. The heart of each machine is a motor—large or small. Without motors and generators our present standard of living would be a dream instead of a reality.

A motor is a device that converts electric power into mechanical power. There are countless uses for motors in industry and in the home. For example, they drive printing presses, clocks, and machine tools. They are also used in servomechanisms and are very important in ventilating and air conditioning systems.

A generator is a device that converts mechanical power into electrical power. Generators can be driven by steam or gas turbines, gasoline or diesel engines, or by electrically operated motors. Generators and motors can be classed as either dc or ac.

This lesson is divided into two parts. The first part covers the operation of dc generators and motors while the second part describes the operation of ac generators and motors. You must study the information presented in Part 1 of this lesson and the material presented in Part 2 before taking the lesson examination which is at the end of Part 2. Be sure that you answer all of the Practice Exercise questions as you proceed through Parts 1 and 2 of the lesson. By doing this, you will insure that you have obtained the best possible understanding of the material covered.

PART 1—DC MOTORS AND GENERATORS

If there is current in the field of a dc motor or generator, and if there is armature rotation caused by some mechanical device, then a dc voltage will be developed at the brushes. If there is also an electrical load connected to the brushes, there will be output current. This dc device is then said to be operating as a **GENERATOR**.

If the generator has dc voltages applied to both the field and brushes, and the generator is used to drive a mechanical load, it is then said to be operating as a **MOTOR**. Motors and generators are sometimes referred to as electrical machines.

DC GENERATOR OPERATION

All electric generators depend upon the principle of **ELECTROMAGNETIC INDUCTION**. THE MOTIONS OF A WIRE ACROSS A MAGNETIC FIELD SETS UP AN ELECTROMOTIVE FORCE (EMF) THAT CAUSES CURRENT. The principle of electromagnetic induction is shown in Figure 1-1. The arrows between the two magnetic poles represent magnetic lines of force, commonly referred to as flux lines. The arrows show the flux lines leaving the north pole of one magnet and entering the south pole of the other magnet. This is the accepted direction for flux lines outside a magnet.

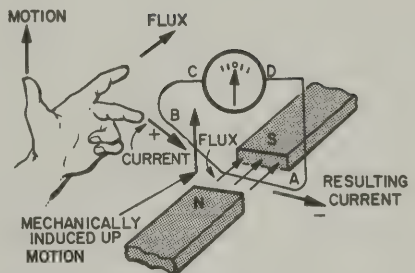


Figure 1-1

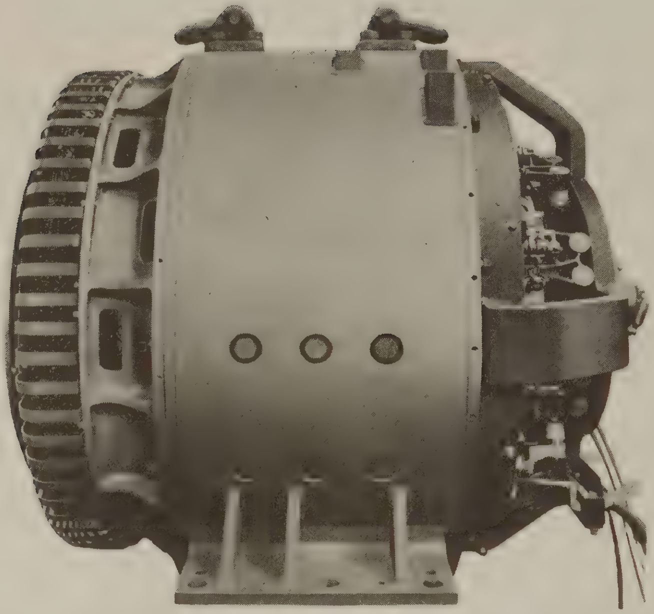
The meter shown in Figure 1-1 is a zero-centered meter. If there is no current in the circuit, the pointer rests on zero. With a positive current, the pointer swings to the right. With a negative current, the pointer swings to the left.

When the wire is not moving, the meter shows that there is no current through the wire. If the wire is quickly moved upward through the magnetic field, the meter swings to one side. The pointer returns to zero when the wire has stopped moving or the wire is moved outside of the magnetic field. When the wire is moved downward through the magnetic field, the pointer again deflects from zero. But this time it moves in the other direction.

By moving the wire in a straight line between the two magnetic poles, or in the same direction as the flux lines, no lines of force are crossed. Even though the wire is moving, the meter shows that there is no current. The reason for this is that the wire does not cross any flux lines. This action demonstrates three important facts:

1. The pointer movement shows that an emf is induced in the wire, which causes a current in the wire.
2. The moving wire must cut across the magnetic lines of force between the poles of the magnets to induce an emf.
3. The meter pointer direction depends upon wire movement. Moving the wire upward swings the pointer one way, and moving the wire downward swings the pointer the other way.

To understand generator operation, we must be able to determine the direction of flux and direction of motion. Using the left hand, as in Figure 1-1, is an easy way to relate these directions. Point the thumb in the direction the wire is mechanically moved. Point the forefinger in the direction of the magnetic flux lines. The middle finger then shows the direction of the resulting current through the part of the wire that is in the magnetic field. The middle finger also points to the negative end of the wire which is in the



This 1000 HP dc traction generator is used in yard switching diesel-electric locomotives. The dc generator has its right end bell cover removed, exposing the brush holders and armature commutator. At the left end of the dc generator there is a three-phase alternator for use with auxiliary equipment.
Courtesy Electro-Motive Division of General Motors

magnetic field. This relationship is known as the three-finger left-hand rule. Applying the three-finger left-hand rule, if the wire shown in Figure 1-1 is moved upward, the induced current in the wire is from point B to point A as shown by the arrow.

To use this rule, you must know two things to find the third. If you know the directions of the flux lines and the wire movement, you can find the direction of current. Or if you know the directions of wire movement and current, you can use the rule to find the direction of the flux lines.

Single-Loop Generator

The arrangement of Figure 1-1 shows the principles of electromagnetic induction. But this simple arrangement cannot produce the large amounts of electrical energy needed in practical circuits. To obtain large amounts of electrical energy and to permit the use of the rotating motion of engines, generators are built with their conductors formed into loops that rotate in magnetic fields.

Figure 1-2 shows a simple electric generator consisting of a permanent magnet and a wire loop. Like the arrangement of Figure 1-1, the simple generator of Figure 1-2 cannot produce a useful amount of electrical energy. It simply shows how a rotating generator works. You will see later how the arrangement of Figure 1-2 resembles a practical generator.

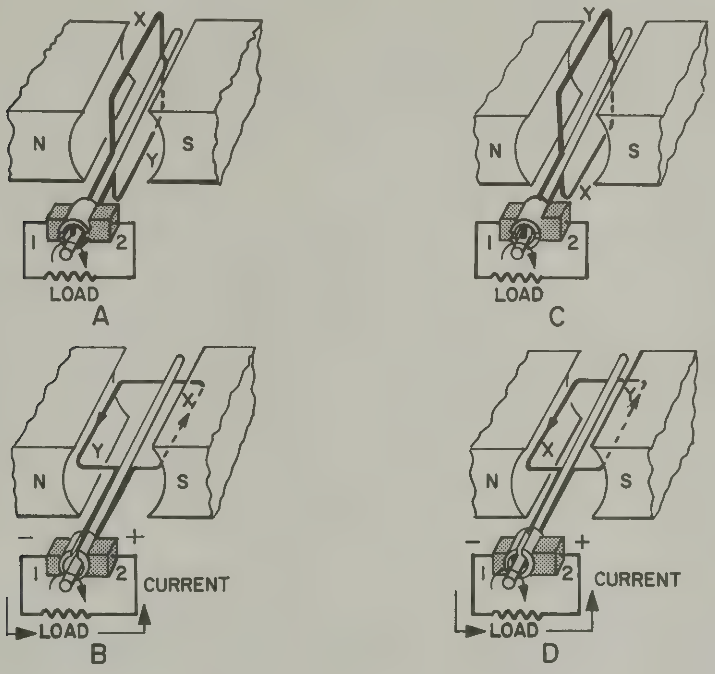


Figure 1-2

The ends of the wire loop shown in Figure 1-2 are connected to a split-ring arrangement called a **COMMUTATOR**. The pieces that make up the commutator are called segments. The wire loop and commutator segments are placed on, but electrically insulated from, a shaft supported by bearings at each end. This complete assembly of loop, commutator, and shaft is called an **ARMATURE**. Pressing against the commutator, carbon or copper brushes form sliding contacts between the loop ends and the external circuit or load.

As previously explained, electromagnetic induction depends upon the motion of the conductor in the magnetic field. In the following explanations assume that the armature rotates at a constant speed in a clockwise direction as shown by the curved arrow near the front end of the shaft in Figure 1-2.

Usually, the wires across the back and front of the loop, and the wires from the loop to the commutator, are outside of the magnetic field and do not have an emf induced in them at any time. At the instant the armature is in the position shown in Figure 1-2A, the loop sides are moving parallel with the magnetic flux, and there is no induction in them. With no induced emf in the loop, there is no voltage between the commutator segments. Therefore, it makes no difference that each brush is touching both segments.

As the loop turns, side X moves to the right and down past magnet pole S, and side Y moves to the left and up past pole N. Simultaneously, the commutator turns so that each brush touches only one segment. When the loop reaches the position shown in Figure 1-2B, the sides of the loop move directly across the magnetic field and the maximum emf is induced in them.

The left-hand rule shows that the electrons flow back along side X and forward along side Y. Tracing the armature circuit from one commutator segment to the other, both emfs cause currents around the loop in the same direction. The voltage between the brushes is the sum of the voltages induced in the loop sides, and brush 2 is positive with respect to brush 1. In the external circuit, electrons leave brush 1 and flow through the load to brush 2.

After the next quarter turn, the loop is in the position shown in Figure 1-2C. The sides of the loop are moving parallel to the flux, and there is no current induced in the wire.

Continued rotation of the armature brings it to the position shown in Figure 1-2D. The loop sides cut directly across the flux, and the induced emf is maximum. The left-hand rule shows that electrons flow back along side Y and forward along side X. As far as the loop sides are concerned, the current direction is opposite to that shown in Figure 1-2B. Because current is in one direction during part of the rotation, and in the opposite direction during the other part of the rotation, THE LOOP CARRIES AN ALTERNATING CURRENT.

Remember, as the loop turns, the commutator also turns. Now side X is connected to brush 1, and side Y is connected to brush 2. In the external circuit, electrons leave brush 1 and flow through the load to brush 2, in the same direction as before. The commutator is a mechanical switch that CHANGES THE ALTERNATING CURRENT IN THE LOOP INTO DIRECT CURRENT IN THE EXTERNAL CIRCUIT.

Another quarter turn of the armature brings it back to the position shown in Figure 1-2A. The loop sides are now parallel to the flux, and no emf is induced in them.

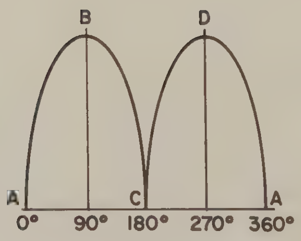


Figure 1-3

The voltage between the brushes is represented by the curve of Figure 1-3. The magnitude of the voltage and the polarity of brush 2 is shown with respect to brush 1 during one complete revolution of the loop. The degree markings below the line represent the angular rotation of the loop in respect to the position of the loop shown in Figure 1-2A. The letters near the curve show the voltage produced when the loop is in the various positions shown in Figure 1-2.

Although the current direction in the load does not change, the induced voltage varies from zero to maximum and back to zero twice during each revolution of the armature. The pulsating component of the dc voltage produced by this generator is reduced by using a generator with more commutator segments.

Multi-Loop Generator

In a practical generator, it is necessary to obtain a greater output than a single turn of wire can produce. This can be accomplished in one of two ways. First, more turns can be added to the loop. The induced and the output voltages are now increased by the added turns. However, the output is still a pulsating dc with two large pulses for each revolution of the armature.

The second way of increasing the output of a generator is to add more loops and commutator segments. This method provides for a more constant output voltage because the peak voltage is produced more than twice in 360° of armature rotation. The commutator segments and loops are equally spaced around the armature. In practical generators, both methods are used together. That is, generators have many loops and many turns of wire per loop with the number of segments corresponding to the number of loops.

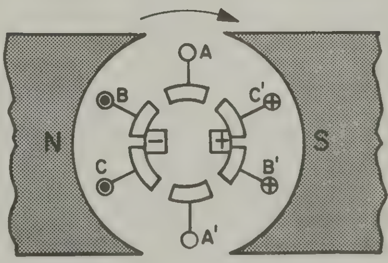


Figure 1-4

The cross section of the three-loop generator of Figure 1-4 shows the effect of adding armature loops. One loop is formed when wire segments A and A′ are connected at the back of the armature, another is formed by the connection of B and B′, etc. The small circles represent the wires which form the sides of the loops. The radial lines are the commutator-to-loop connections. To make the figure simple, the brushes are shown inside the commutator; however, you must remember that the brushes actually bear against the outside of the commutator.

When the armature is turning in a clockwise direction, the left-hand rule shows that the current is out of the paper in the coil sides near the N pole. This condition is shown by the small dots placed in loop sides B and C to represent current which is in a direction out of the paper toward you. You can think of the dot as the point of an arrow representing the direction of current. In loops B′ and C′, the crosses represent current into the paper away from you. You can think of the crosses as the fins of an arrow representing the direction of current.

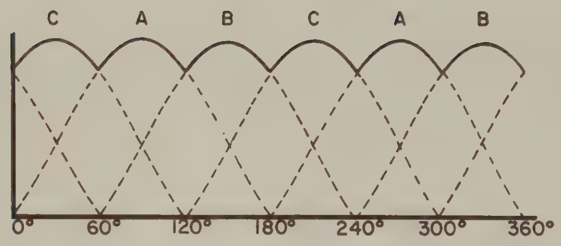


Figure 1-5

As the armature turns, the induced voltage across each coil changes as shown by the curves of Figure 1-5. Properly positioned, the brushes make contact with one pair of segments when the induced voltage in the associated loop is near maximum. The brushes keep contact while the voltage rises to maximum and then decreases slightly. Then the brushes contact the following pair of segments. The widths of the commutator segment and the brushes are chosen so that the loop voltages are almost equal when the brushes contact the second pair of segments. The actual output from the generator is shown by the wavy, solid line across the tops of the curves of Figure 1-5.

The coil arrangement of Figure 1-4 is poor because the induced output emf occurs only in the coil to which the connections are made. This arrangement is called an "open-circuit winding" because there is no continuous path between all of the loops. For efficiency, the armature coils are connected so that all of the induced voltages are series-aiding across the brushes.

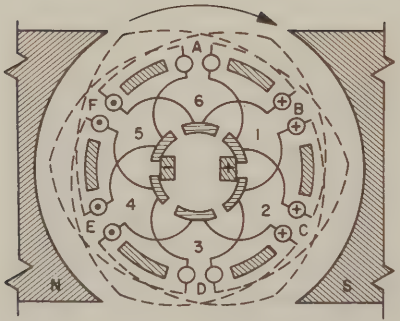


Figure 1-6

Figure 1-6 shows the pictorial diagram of a two-pole, six-coil generator in which all of the loops are connected in series. The outer curved segments represent the armature core, while the spaces between these segments represent the armature slots in which the windings are placed. The small circles in the armature slots represent the coil sides that extend from the front to the back of the armature. As in Figure 1-4, the dots and crosses within the circles indicate current in the sides of the loops. Extending from the outer ends of the coil sides, the dashed curved lines represent the wires across the back of the armature. The solid curved lines represent the connections from the loop sides to the commutator segments.

Regardless of the connections, the loops or coils must be placed so that when one side is near the N pole, the other side is near the corresponding part of the S pole. This means that in the two-pole generator of Figure 1-6, the sides of a given coil must occupy slots on opposite sides of the armature. For example, armature slot A is directly opposite armature slot D. Starting at commutator segment 1, you can trace a complete circuit to the coil side in armature slot A, along the dashed line to the coil side in armature slot D, and then to commutator segment 2.

To improve the efficiency, the coils are arranged so that two coils pass through each slot. Thus, the two circles in armature slots A and D represent the sides of two separate coils.

To provide the desired output, the loop ends are attached to commutator segments which are alongside each other. The coils are then connected in series between the brushes. To illustrate this condition, a complete circuit may be traced from the +brush to commutator segment 2, through the coil in armature slots B and E to commutator segment 3, through the coil in slots C and F to commutator segment 4 and the −brush. Simultaneously, a circuit can be traced from the +brush to commutator segment 1, through the coil in slots C and F to commutator segment 6, through the coil in slots B and E to commutator segment 5 and the −brush. Thus, between the brushes there are two paths with two coils each.

When the armature in Figure 1-6 rotates slightly clockwise so that the positive brush is contacting only commutator bar 1 and the other brush is on bar 4, then the current path is a little longer. The path is from bar 1 to slots A and D to bar 2. From then on, the path travels to bar 4 as shown in the preceding paragraph. This time current is through at least one conductor in each slot.

In the position shown, the brushes are in contact with commutator segments 1 and 2, and segments 4 and 5. The coils in armature slots A and D are shorted. These coils are at the point of zero induction, and the shorting has no effect on the generator output.

The coil arrangement of Figure 1-6 provides two parallel paths between brushes and is generally known as a **SIMPLEX WINDING**. It also is known as a "closed-circuit winding" because, starting at commutator segment 1, you can trace a path through all of the conductors in all of the armature slots until you reach segment 1 again.

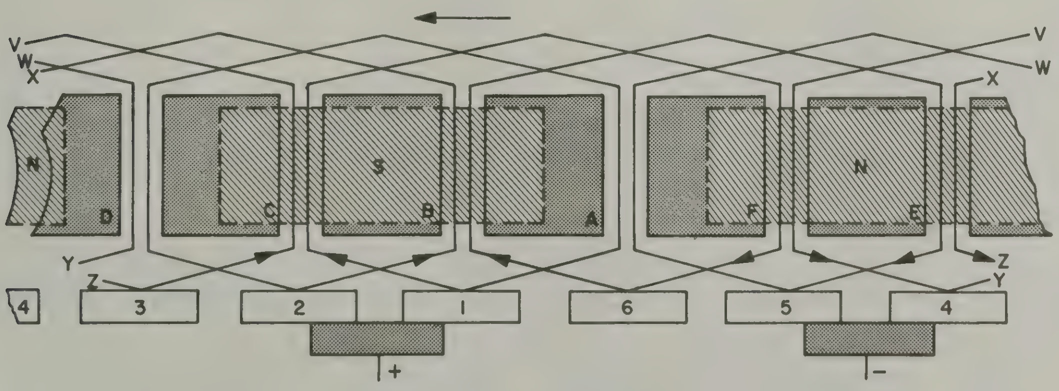


Figure 1-7

So that you can see it more clearly, the armature of Figure 1-6 is shown laid out flat in Figure 1-7. The armature slots and commutator segments correspond to those of Figure 1-6. The brushes are placed in the same relative positions. Letters at each end of the figure show the continuation of the various coils. The dashed rectangles show the positions of the N and S magnetic poles.

With the armature coils moving in the direction indicated by the arrow at the top of the figure, the direction of current is as shown by the arrowheads on the coils. Electrons flow backward along the side of slot B, forward along the side of slot E, backward through slot C and forward through slot F, thereby making commutator segment 2 positive and commutator segment 4 negative.

Simultaneously, electrons flow backward along the coil side in slot C, forward along the slot F coil side, backward through slot B, and forward through slot E. This makes commutator segment 1 positive and commutator segment 5 negative. Because the brush on the left side of Figure 1-7 is in contact with commutator segments 1 and 2, it is positive. Because the brush on the right side of Figure 1-7 is in contact with commutator segments 4 and 5, it is negative.

The arrowheads show that the currents in the coils of armature slots B, C, E and F are in such a direction as to aid each other. Therefore, the voltage between the brushes is equal to the sum of the emfs induced in the coils connected between segments 2 and 4, and segments 1 and 5. The induced emf in one coil increases at very nearly the same rate that the induced emf decreases in the other coil. Therefore, the generator output voltage is held nearly constant and a greater average power output results.

Generator Ripple

Direct current generators that supply operating voltages to transmitters, receivers and other electronic equipment have a large number of armature slots and commutator segments so that the output will be as pure dc as possible. Even then, a small ac component or ripple remains in the generator output. You can trace this ac component to three main sources: (1) the armature slots, (2) the commutator, and (3) the brushes.

SLOT RIPPLE is caused by the interruption of the magnetic flux when the slot passes the pole piece. This causes a surge of field flux that varies the induced voltage in the armature conductors. **COMMUTATOR RIPPLE** is caused by uneven voltage distribution between commutator segments. **BRUSH RIPPLE** is caused by poor contact between the brush and the commutator. A worn commutator or poor adjustment of the brush spring tension usually causes brush ripple.

As previously mentioned, most applications require that the dc generator output is to be as free from a ripple component as possible. For instance, generator ripple that appears in the input stages of a transmitter is very undesirable. These voltage variations are amplified millions of times along with the modulating signals before they are radiated from the antenna. Besides the steps taken in the design and maintenance of generators, many transmitters include ripple filters such as those used in ac power supplies. This filter is of the low-pass pi (π) type, which does not pass voltage variations above a particular frequency, and passes voltage variations below that particular frequency. Direct current, which is equivalent to zero frequency, is easily passed by such a filter while the ripple component is not.

Generator Types

The dc generator is used extensively in automotive, aeronautical, and marine installations as well as many industrial applications. Except for some small size and special purpose generators that use permanent magnets, most dc generators employ electromagnets to produce the magnetic field flux. For proper operation, the magnetic field polarity must not change; therefore, the windings are supplied with direct current. There are two common sources of this direct current. One is a small dc generator mounted on the same base and mechanically connected to the shaft of the larger generator. With this arrangement, the generator is said to be **SEPARATELY EXCITED**. The smaller generator that supplies the field current is called an **EXCITER**.

However, as direct current is available at the brushes, many generators use the armature as the source of field energy, and are called **SELF-EXCITED GENERATORS**. The starting action is explained as follows. Once a generator is used, the iron frame and pole pieces retain a small amount of magnetism. Known as "residual magnetism," this small magnetism induces a small emf in the armature when it is turned. The resulting low current in the field coils increases the flux. This induces a higher armature emf and increases the field current. The action continues until the generator output builds up to its rated value.

Depending upon how the field winding is connected to the armature, there are three classes of self-excited generators: (1) shunt, (2) series, and (3) compound.

Shunt Generator

Figure 1-8 shows a simplified form of a two-pole generator in which a single field winding produces the required magnetic flux. As shown, one end of the field winding and one brush connect to the +output terminal, while the other

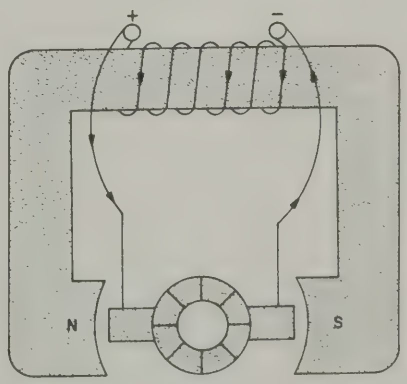


Figure 1-8

end of the field coil and the other brush connect to the −output terminal. Thus, the field coil and the armature are in parallel across the output terminals; and this arrangement is known as a **SHUNT GENERATOR**. So that it does not take too much of the output current, the field winding is wound with many turns of small wire to give it a sufficiently high resistance.

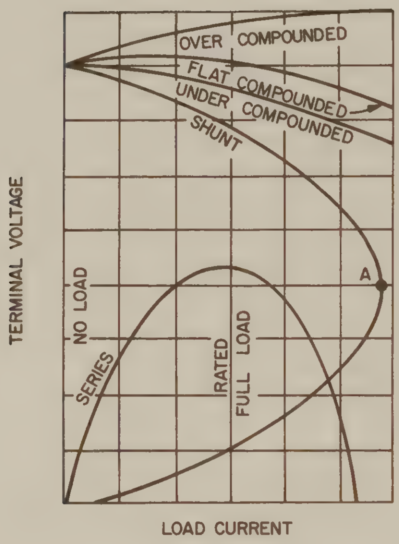


Figure 1-9

When the shunt generator is started, the residual magnetism induces a voltage in the armature conductors. Applied across the field winding, this voltage causes a current that increases the magnetic flux and the induction. Thus, the generator builds up to its normal voltage, even if no external load is connected to its terminals.

With the armature turning at a constant speed and delivering a constant current to the external load, the generator voltage remains almost constant. However, if the load current is increased, the resulting increase of voltage drop across the armature coils and the brush-to-commutator contact resistance cause the voltage at the output terminals to drop as shown by the SHUNT curve of Figure 1-9.

Because the field winding is connected across the armature, the decrease of armature voltage lowers the field current and its resultant flux. This decreases the terminal voltage more rapidly than if the drop were caused entirely by the armature coil and brush-to-commutator contact resistances. As the load resistance is decreased, the load current increases, and the terminal voltage drops rapidly until it reaches point A shown in Figure 1-9.

Further decrease of load resistance causes a rapid decrease of terminal voltage, and a decrease of load current. If the load resistance is decreased to zero, the field winding is short-circuited and there is no field current. At this point, the emf induced in the armature is due entirely to the residual magnetism. As this voltage is quite low, the load current is small and there is no damage to the generator.

Series Generator

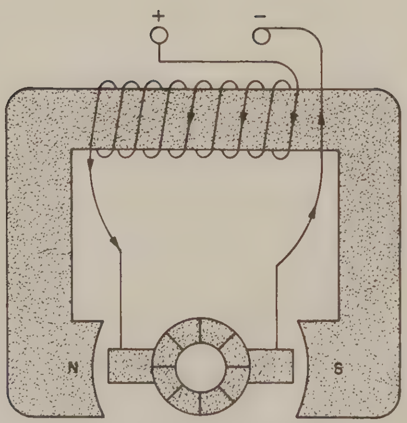


Figure 1-10

Instead of connecting a high-resistance field in parallel with the armature as shown in Figure 1-8, a low-resistance field may be connected in series with the armature to produce the **SERIES GENERATOR** shown in Figure 1-10. Like the shunt generator, the series generator retains a small amount of residual magnetism in the frame and pole pieces. When the generator is started, the residual magnetism induces a low voltage in the armature. However, the series generator voltage does not build up until a load is connected and there is current in the field winding.

With an external load, there is current in the field coil, and the magnetic flux increases. As a result, the generator voltage builds up as shown by the SERIES curve of Figure 1-9. With the armature turning at a constant speed and delivering a constant current to the load, the terminal voltage remains constant. However, if the load resistance is decreased, the load current is increased, and the resulting increase of magnetic flux induces a higher armature voltage. This continues until the rated full-load conditions are reached.

Any further increase of load current merely saturates the magnetic field and does not increase the induced voltage. Simultaneously, the higher voltage drop across the armature, field coil, and brush-to-commutator contact resistances causes a decrease of terminal voltage. If the load resistance is decreased to zero, the machine is short-circuited and the terminal voltage is zero, but the circuit current is high.

Compound Generator

In most electric power systems, constant voltage is needed under varying load current conditions. To meet these needs, both series and shunt fields are used. Such an arrangement is known as a **COMPOUND GENERATOR**. Figure 1-11 shows a simple **CUMULATIVELY-COMPOUNDED GENERATOR** in which a series winding flux aids the shunt winding flux. With this arrangement, an increase of load current causes an increase of series-field current. The added flux prevents the total field strength from changing to any great extent.

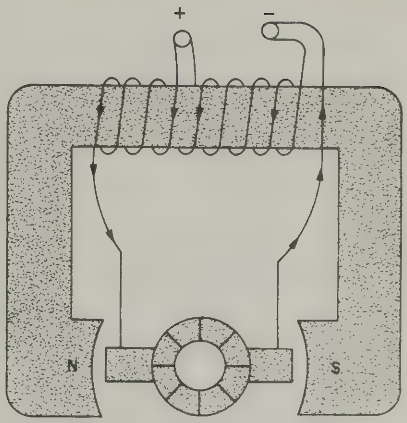


Figure 1-11

Because its effect varies with the load current, the series-field winding can be made for three different conditions of voltage regulation. When the effect of the series-field winding does not completely overcome the loss of shunt-field winding excitation, an **UNDER-COMPOUNDED GENERATOR** condition results. The voltage at rated full load is less than no load, as shown by the UNDER-COMPOUNDED curve of Figure 1-9.

If the series-field winding flux neutralizes the loss of shunt-field winding flux so that the no-load and rated full-load voltages are the same, a **FLAT-COMPOUNDED GENERATOR** condition results. As shown by the FLAT-COMPOUNDED curve of Figure 1-9, the terminal voltage is almost constant between no load and rated full load, and then decreases slightly beyond rated full load.

When the series field increases the total flux, an **OVER-COMPOUNDED GENERATOR** condition results. The voltage at rated load is higher than at no load as shown by the OVER-COMPOUNDED curve of Figure 1-9.

For certain applications, the series field connections are reversed so that the flux produced by the series field reduces the flux produced by the shunt field. With this arrangement, a **DIFFERENTIALLY-COMPOUNDED GENERATOR** condition results. Because of the opposition of the two fields, the terminal voltage drops more rapidly than that of a shunt generator when the current drawn by the load increases.

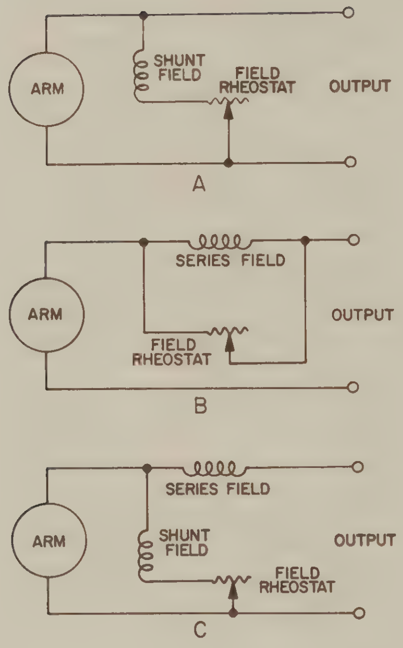


Figure 1-12

Voltage Control

The output voltage from a dc generator is controlled manually by a variable resistor called a **FIELD RHEOSTAT**. For a shunt generator, the rheostat is connected in series with the field winding, as shown in Figure 1-12A. For any given armature speed, a change of field current causes a corresponding change of magnetic flux and output voltage. Increasing the field rheostat resistance lowers the field current and output voltage. Conversely, decreasing the field rheostat resistance raises the field current and output voltage.

In a series generator, the field rheostat is connected in parallel with the field winding as shown in Figure 1-12B. Decreasing the field rheostat resistance lowers the field current and output voltage. Conversely, increasing the field rheostat resistance raises the field current and output voltage.

As previously explained, a compound generator provides a degree of automatic voltage regulation. For manual voltage control, the field rheostat is connected in series with the shunt-field winding as shown in Figure 1-12C

DC MOTOR OPERATION

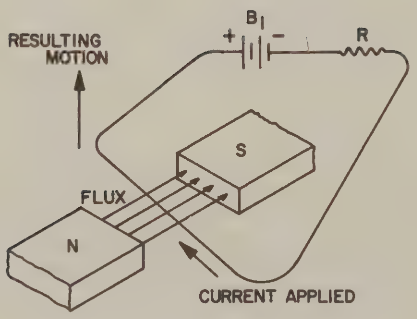


Figure 1-13

When Michael Faraday was performing his experiments that led to the discovery of electromagnetic induction, he observed that a wire held in a magnetic field moved slightly when its ends were connected to a voltage source. Known as the "motor effect," this action is shown in Figure 1-13. Battery B_1 supplies the applied voltage, and resistor R limits the current in the wire. With current and flux in the direction shown, the wire tends to move upward. This is the basic principle on which all electric motors operate.

Notice the similarity between the simple generator of Figure 1-1 and the simple motor of Figure 1-13. In the generator of Figure 1-1, the motion is supplied and current is produced. In the motor of Figure 1-13, the current is supplied and motion is produced.

The following Practice Exercise questions cover the subjects which you have just studied. They are:

DC GENERATOR OPERATION
- SINGLE-LOOP GENERATOR
- MULTI-LOOP GENERATOR
- GENERATOR RIPPLE
- GENERATOR TYPES
- VOLTAGE CONTROL

1. The magnets and wire shown in Figure 1-1 form a simple generator. True or False?

2. Outside a magnet, flux travels from a (a) south pole to a north pole, (b) north pole to a south pole.

3. The direction of induced current in a wire passing through a magnetic field depends (a) only upon the direction of flux, (b) only upon the direction of wire movement, (c) upon the directions of both flux and wire movement.

4. The split-ring arrangement shown in Figure 1-2 is called a (a) brush, (b) commutator.

5. What advantage does a multi-loop generator have compared to a single-loop generator?

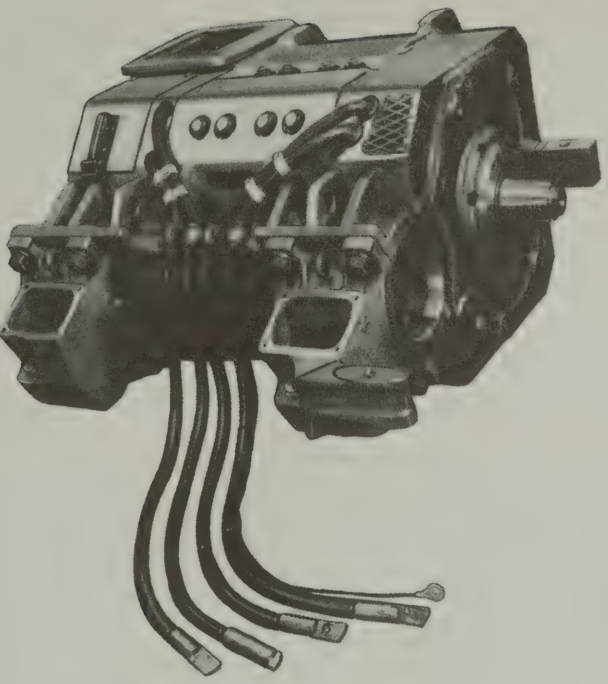
6. A generator with a closed-circuit winding provides a more constant output voltage than a similar generator with an open-circuit winding. True or False?

7. What are three sources of ripple in a generator?

8. Which type of generator provides the most constant output voltage under varying load conditions?

9. **In a series generator, output voltage control is obtained by placing a rheostat (a) in series with the field winding, (b) in parallel with the field winding.**

10. **In a shunt generator, output voltage control is obtained by placing a rheostat (a) in series with the field winding, (b) in parallel with the field winding.**



This series wound dc traction motor is used in yard switching diesel-electric locomotives. This dc motor can be operated at up to 750 HP.
Courtesy Electro-Motive Division of General Motors

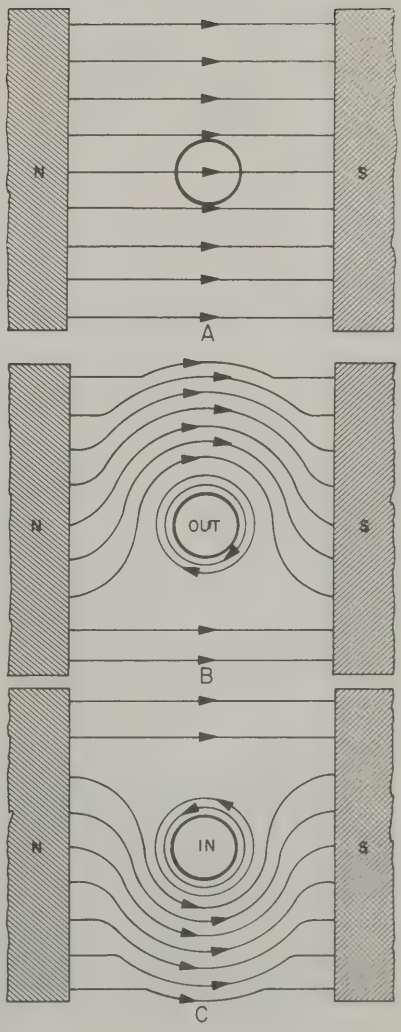


Figure 1-14

To understand why the wire of Figure 1-13 moves, let's look at Figure 1-14. Figure 1-14A shows the uniform magnetic field produced between the N and S poles of a pair of magnets. The circle near the center of the field represents the cross section of a length of wire that crosses the field. If there is no current through the wire, it does not move.

If the wire is part of an electric circuit and the electrons move in the direction out of the page, the resulting magnetic field encircles the wire in a clockwise direction, as shown in Figure 1-14B. Two magnetic fields in the same space interact. Above the wire, the flux lines of the two fields are in the same direction, while below the wire, they are in opposite directions. As a result, some of the lines that did pass below the conductor are bent upward and are forced to pass over it. Like stretched rubber bands, these flux lines try to straighten out and return to their normal positions. However, as they do, they are opposed by the flux lines around the conductor. Because of interaction of the flux lines, there is a force on the wire that moves it downward.

The direction of the force on the wire depends on the direction of the magnetic flux and the direction of the current in the wire. Figure 1-14C shows what happens when the current is reversed, so that the electrons flow into the wire instead of out. The magnetic field produced by the current circles the wire in a counterclockwise direction. The resulting flux interactions cause some of the flux lines that passed above the wire to be bent downward and pass below the wire. Because of the interaction of the flux lines, there is a force on the wire that moves it upward.

In Figures 1-14B and 1-14C, there are three factors to consider:

1. The direction of the magnetic field,

2. The direction of current in the conductor, and

3. The direction of wire movement.

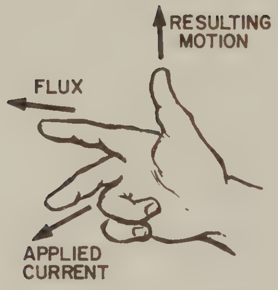


Figure 1-15

These three factors are related by the thumb, forefinger, and middle finger of the right hand as shown in Figure 1-15. This relationship is known as the three-finger right-hand rule. The thumb shows the direction of wire movement in the magnetic field. The forefinger shows the direction of the magnetic flux, and the middle finger shows the current direction in the conductor.

WHEN WORKING WITH A MOTOR USE THE RIGHT-HAND RULE. WHEN WORKING WITH A GENERATOR USE THE LEFT-HAND RULE.

Single-Loop Motor

The actions of Figures 1-14B and 1-14C may be combined by placing a wire loop in a magnetic field so that one side is close to the N pole and the other side is close to the S pole, as shown in Figure 1-16A. When the loop is connected to a source voltage, the current is in one direction past the N pole and in the opposite direction past the S pole. As shown in Figure 1-16A, the resulting field distortion pushes one side of the loop downward and the other side upward.

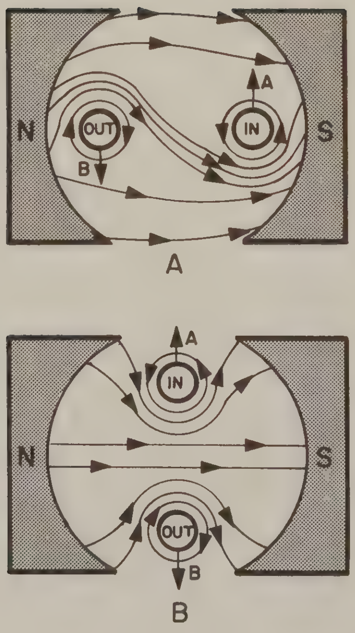


Figure 1-16

With the directions of current and flux as shown, the loop will turn until it reaches the position of Figure 1-16B. At this point, the forces are directly opposed and cannot cause further rotation. If the loop is turned further, the positions of the wires are reversed with respect to those of Figure 1-16A, and the resulting forces move the loop back to the position of Figure 1-16B.

For continuous rotation in one direction, the loop current direction is reversed at the instant the sides reach the position of Figure 1-16B. To do this, the loop ends are connected to segments of a commutator, as shown in Figure 1-17.

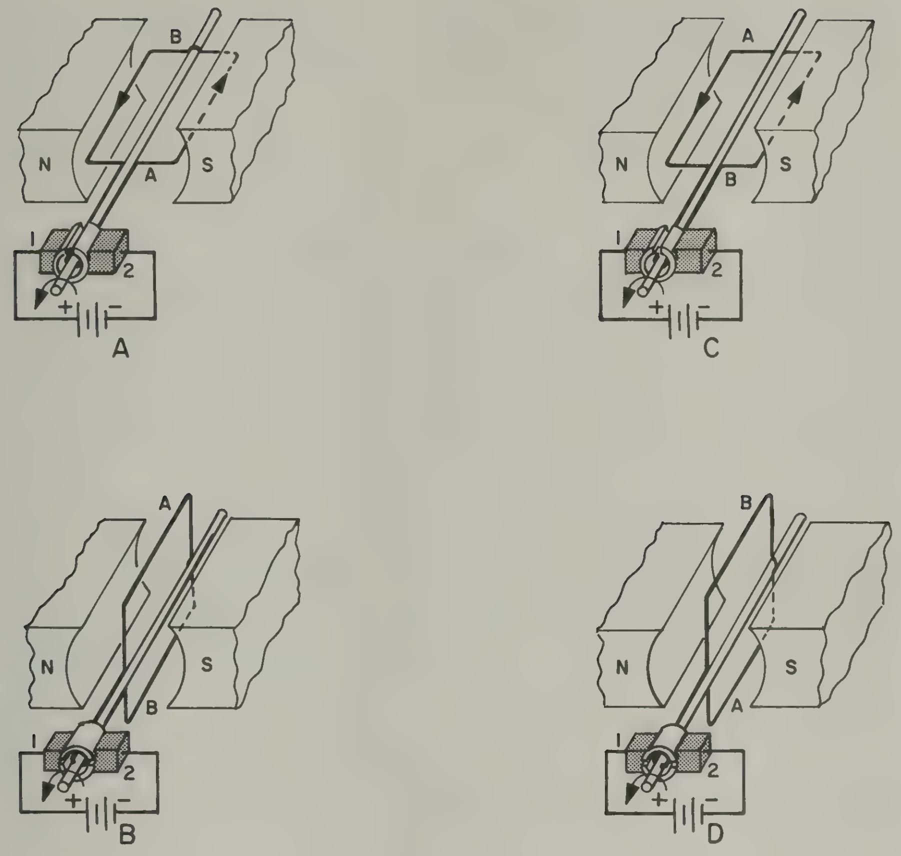


Figure 1-17

With the brushes connected to a battery, and the loop positioned as shown in Figure 1-17A, electrons flow to the back of the loop along side A and to the front of the loop along side B. This produces the conditions of Figure 1-16A, and the armature turns in a counterclockwise direction.

An instant before the armature reaches the position of Figure 1-17B, the brushes short-circuit the loop and reduce its current to zero. (The condition of Figure 1-17B also short-circuits the battery. This condition is momentary and does not damage the battery.) With no current in the loop, there is no force on the conductors. The momentum of the armature carries it past the position of Figure 1-17B toward that of Figure 1-17C.

When the short circuit is removed, electrons again flow in the loop. But now the commutator has reversed the loop connections, so that the current direction is to the back of the loop along side B and to the front of the loop along side A. Thus, side B is forced up and side A is forced down, and the armature is turned in the same direction as before. This action continues until the loop reaches the position of Figure 1-17D and the loop is short-circuited by the brushes. Again carried by loop momentum, the loop moves toward the position of Figure 1-17A and the action starts over again.

Torque

Any force that causes rotation is known as **TORQUE**, and is measured in pound-feet to distinguish it from the foot-pounds used to represent work. In a motor, torque is produced by the interaction of the field flux and the flux surrounding the current-carrying armature conductors. The amount of torque depends on the armature current, field strength, number of active armature conductors, and the distance from the shaft center to the center of the conductor which produces the torque.

In all motors, the number of armature conductors and their distances from the shaft center are fixed; therefore, the torque produced depends on the field strength and armature current. This relationship is very important, as it explains why the torque changes with a change in load in different types of motors. Torque is actually proportional to the field strength multiplied by the armature current.

Counter EMF

When the motor of Figure 1-17 is connected to a battery as shown, the armature spins in a counterclockwise direction. However, as soon as the armature begins to move, the loop sides cut the magnetic flux and a voltage is induced in them. If you apply the left-hand rule, the direction of induction in the loop sides is opposite to that shown by the arrowheads. Trying to force electrons around the circuit in the reverse direction, the induced voltage opposes the battery voltage. This opposing voltage is called **COUNTER EMF**, abbreviated **cemf**.

The effect of the counter emf in a motor is to oppose the supply voltage and thus lower the armature current. However, the counter emf can never equal the applied voltage. If it did, the two voltages would cancel each other and there would be no current in the armature. As a result, the torque would drop to zero and the armature would stop. In practice, counter emf is always a little less than the supply voltage.

The induced emf varies with the rate of flux cutting. As the armature turns faster, more counter emf is produced, which results in a lower armature current. Conversely, as the armature turns slower, less counter emf is produced, which results in a higher armature current. A change of field strength also affects the counter emf. A stronger field increases the counter emf and lowers the armature current, while a weaker field reduces the counter emf and increases the armature current.

Multi-Loop Motor

Like the single-loop generator of Figure 1-2, the single-loop motor is very inefficient. It produces only two torque pulses for each complete revolution of the armature. The operation is smoother and more efficient if a number of loops are spaced uniformly around the armature.

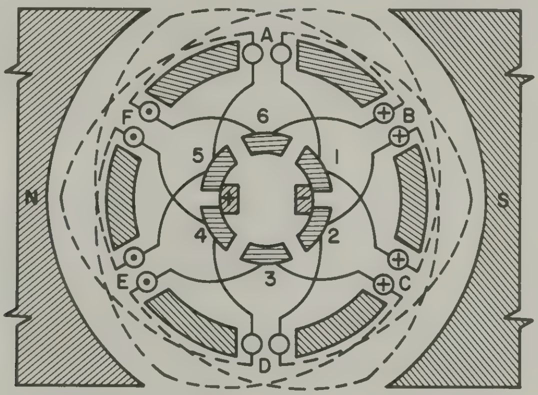


Figure 1-18

A multi-loop motor is shown in Figure 1-18. Notice that this motor is very similar to the multi-loop generator of Figure 1-6. The small circles in the armature slots represent the sides of the armature windings. That is, they represent a cross section of the wires which form the sides of the armature loops. The crosses in the circles represent current to the back of the armature windings along the sides of the armature loops. The dots in the circles represent current to the front of the armature windings along the sides of the armature loops.

The solid curved lines represent the connections between the armature loop sides and the commutator segments. The curved, dashed lines represent wires of the armature loops which pass across the back of the armature.

Electrons enter the motor at the negative brush and flow to commutator segments 1 and 2. From segment 1, electrons flow through the coil in armature slots C and F to commutator segment 6. From segment 6, electrons flow through the coil in slots B and E to commutator segment 5. The second path is from segment 2 through the coil in armature slots B and E to segment 3 and through the coil in armature slots C and F to segment 4.

When current enters the motor at the negative brush it passes through the windings to the positive brush as explained, and returns to the external source. As in the generator, the brushes are placed so as to short-circuit the coils that are moving parallel to the magnetic flux. No voltage is induced in the coils when they are in this position.

Analyzing the motor with the right-hand rule, the magnetic fields set up by the armature loops react with the fields from the pole magnets, which cause the armature to turn counterclockwise. The torque produced by this motor is the result of many armature loops or windings. This motor is more powerful and provides smoother operation than a single-loop motor. In general, a motor with many windings has more power than a motor with only a few windings.

Motor Types

Direct current motors are sometimes used to drive loads like electric buses, delivery trucks and locomotives. When used to propel such vehicles, the dc motors are called traction motors. Other uses of dc motors include the operation of machinery which has a variety of speed and torque demands. Their variable speed characteristics make dc motors more suitable than ac motors for certain applications. Like generators, motors are either shunt, series or compound, depending on how the field winding is connected to the armature.

Shunt Motor

A **SHUNT MOTOR** and a shunt generator have the same circuit arrangement. As shown in Figure 1-8, the field is connected directly across the line, in parallel with the armature. As in the shunt generator, the field coils have a large number of turns of small wire, and the armature coils have a few turns of heavy wire.

When the motor is in operation, the small field current produces a magnetic flux that stays fairly constant under all load conditions. Simultaneously, the flux cuts the armature conductors and induces a counter emf in them that is proportional to the field strength and the armature speed. Because the counter emf opposes the supply voltage, the difference between them is the effective voltage that produces armature current.

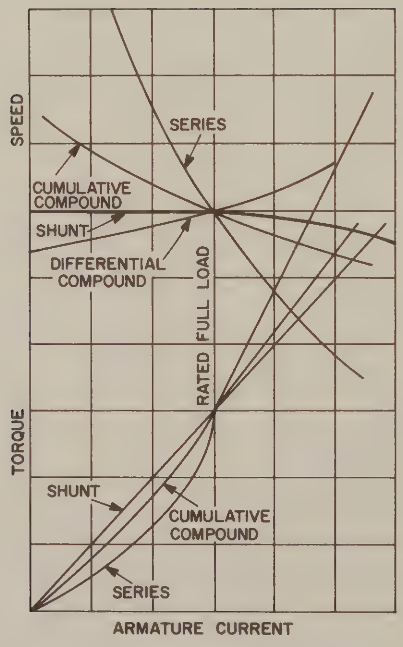


Figure 1-19

As previously explained, the torque developed by a motor is proportional to the field strength and the armature current. Figure 1-19 shows the speed and torque characteristics of shunt, series and compound motors. Starting at the lower left corner, the torque and speed values increase vertically, while the armature current values increase horizontally.

The torque versus armature current curve of the shunt motor is essentially a straight line because the field strength is constant. Thus, torque varies linearly with armature current in the shunt motor. The speed curve for a shunt motor shows that it has a definite no-load speed. With no mechanical load, just a little current is needed to produce a torque that causes the armature to turn at a speed at which the counter emf approaches the supply voltage. If the armature speed increases slightly, the counter emf is increased also. The result is a decrease of effective voltage, armature current and torque so that the armature slows down slightly. If the armature speed decreases slightly, the counter emf decreases and permits a higher armature current. The greater torque increases the armature speed slightly. In practice, these actions automatically balance so that the motor runs at some definite speed and draws a certain amount of current from the source.

When the mechanical load is increased, the armature slows down slightly. As it does, the counter emf decreases and permits the armature current to increase. The resulting increase of torque tends to hold the speed at its original value. Thus, a shunt motor does not run away when the load is removed, provided the field current remains the same. For this reason, A SHUNT MOTOR IS CONSIDERED TO BE A CONSTANT-SPEED MOTOR, even though its speed does decrease slightly with increase of load.

Series Motor

SERIES MOTORS and series generators both have their armature and the field windings connected in series between the external terminals, as shown in Figure 1-10. The field winding has relatively few turns of heavy wire so that it is capable of carrying the rated armature current.

Remember that the torque developed by any motor is proportional to the product of the armature current and field flux. The field flux of a series motor is normally doubled when the current is doubled; therefore, the torque varies almost as the square of the current. This condition is illustrated by the SERIES curve of Figure 1-19.

With no mechanical load, a small armature current produces a torque that causes the counter emf and speed to increase. As in the shunt motor, an increase of counter emf causes a reduction of armature current. But, in a series motor, the reduction of armature current lowers the field current and flux. With a weaker field current, the armature speed increases to induce a balancing counter emf. The resulting decrease of field current causes a further increase of armature speed. This action can continue until the armature coils are thrown from the core by centrifugal force. For this reason, many series motors, especially the larger ones, are never operated without a load, nor installed so that the load can be accidentally removed.

When the mechanical load is increased, the armature slows down; this reduces the counter emf and increases the armature current. The higher field current produces a stronger magnetic flux, and the balancing counter emf is induced at a lower armature speed. Thus, as the load on a series motor is increased, the current and torque increase and the armature speed decreases as shown by the curves of Figure 1-19. For any given load, a series motor will run at some definite speed, BUT THE HEAVIER THE LOAD, THE SLOWER THE SPEED. Often, A SERIES MOTOR IS CONSIDERED TO BE A CONSTANT-HORSEPOWER MOTOR.

Compound Motor

A CUMULATIVELY-COMPOUNDED MOTOR has both shunt and series fields that aid each other as shown in Figure 1-11. Therefore, its characteristics lie between those of the shunt and series motors. As shown by the curves of Figure 1-19, THE SPEED AND TORQUE OF A CUMULATIVELY-COMPOUNDED MOTOR VARY WITH LOAD MORE THAN A SHUNT MOTOR AND LESS THAN A SERIES MOTOR.

Differentially-compounded motors tend to speed up with a steadily increasing load (again see Figure 1-19), and the speed can increase until the armature flies apart. Consequently, this type of motor is seldom used in industry. It is possible to design a differentially-compounded motor that has exactly the same speeds at no load and at full load.

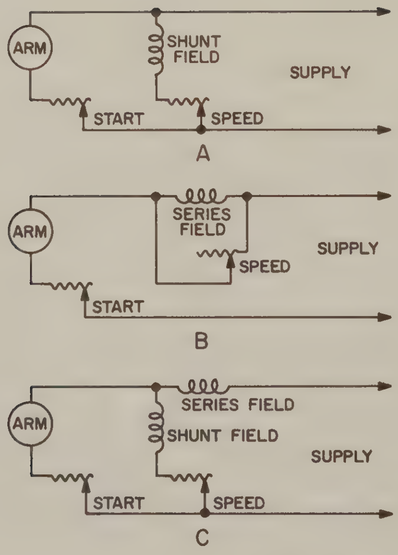


Figure 1-20

Starting DC Motors

As previously mentioned, the armature current of a motor is controlled by the counter emf, which is proportional to the field strength and armature speed. When the armature is stationary, there is no counter emf, and the current is limited only by the low resistance of the armature coils. If the full supply voltage is applied across the armature, the resulting surge of current may destroy the coils. Also, the sudden torque developed by the current surge may damage the motor or its load.

To prevent this action, a rheostat is usually connected in series with the armature. Labeled START in Figure 1-20A, this rheostat is set to maximum resistance before the supply circuit is connected. The added resistance limits the armature current to a safe value. As the armature picks up speed, the induced counter emf reduces the current. The series resistance of the rheostat is slowly removed from the circuit to permit the current, speed and torque to increase to normal. In practice, the rheostat is mounted in a separate enclosure called a starting box or starter. Figure 1-21 shows the starter arrangement used with shunt motors. Similar arrangements are used with series and compound motors.

The starter rheostat contains several series-connected resistors, the ends of which are brought out to a row of stationary contacts. The last contact at the right is connected to terminal A, while the contact at the other end of the resistor string is connected to terminal F through the NO-VOLTAGE RELEASE electromagnet. The circuit from terminal −L to the stationary contacts is completed by a pivoted arm. The SPRING near the pivot returns the MOVABLE ARM to the OFF position when the arm is released by the electromagnet.

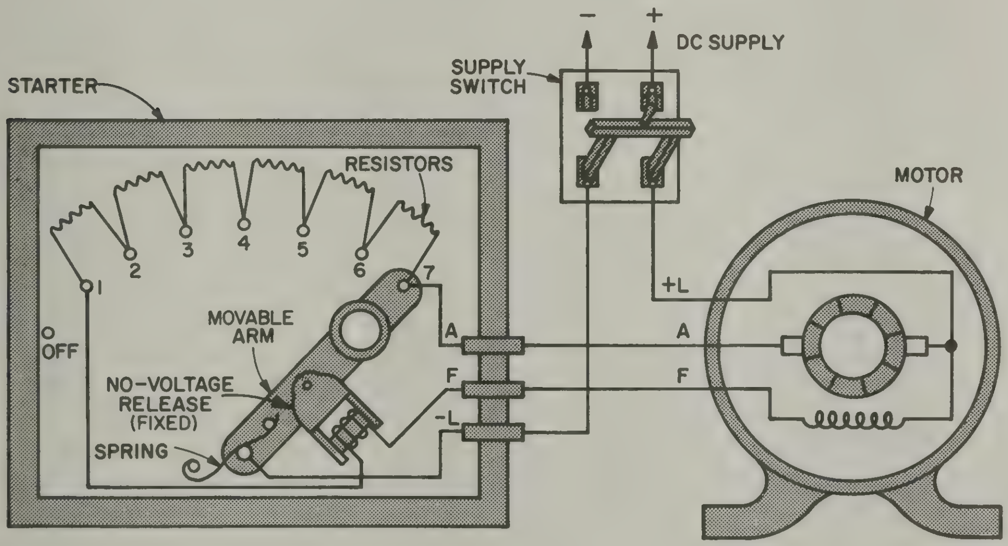


Figure 1-21

The motor has three terminals so it can be used with the starter. The +L terminal connects to one brush and one end of the field, terminal A connects to the other brush and terminal F connects to the other end of the field. The electric circuit is completed by connecting the starter and motor terminals A and F together, and the +L and −L terminals to the dc supply through the SUPPLY SWITCH.

To start the motor, the SUPPLY SWITCH is closed and the MOVABLE ARM is moved from OFF to the first contact, In this position, the MOVABLE ARM completes a circuit from the −supply wire through the supply switch, terminal −L and the MOVABLE ARM to the first stationary contact.

From this point, there are two current paths. One is through the NO-VOLTAGE RELEASE electromagnet, starter terminal F, motor terminal F, the field winding, motor terminal +L and the SUPPLY SWITCH to the +supply line. The other path is through the resistors, starter terminal A, motor terminal A, the armature, motor terminal +L and the SUPPLY SWITCH to the +supply line.

These circuits place the line voltage directly across the field and place the starter resistors in series with the armature. As the armature speed increases, the MOVABLE ARM is moved from one contact to the next, which removes the series resistors one by one. When the MOVABLE ARM reaches the position of Figure 1-21, it connects the armature directly across the supply, and connects the starter resistors in series with the field resistance. The starter resistances are so low that they have very little effect on the field current. This is possible because the field resistance is much higher than the resistance of the starter resistors.

In many starter units, the starter resistors are not built to continuously carry the armature current. If the starter arm is held on one contact too long, the resistors can overheat and burn up.

The NO-VOLTAGE RELEASE electromagnet prevents the arm from being left in the running position (Position 7) when the motor is shut off or when the dc supply falls below a certain voltage. Carrying the field current, the NO-VOLTAGE RELEASE electromagnet winding produces a magnetic field that attracts a piece of soft iron attached to the MOVABLE ARM and holds the MOVABLE ARM in the running position. If the DC SUPPLY is disconnected or sufficiently reduced, the SUPPLY SWITCH opened, or the field circuit broken in any way, the magnetic field dies out, which allows the SPRING to return the MOVABLE ARM to the OFF position. This disconnects the motor from the DC SUPPLY.

Motor Speed Control

With a given load and supply voltage, a dc motor runs at a speed such that the armature current produces enough torque to meet the demand of the load. In many situations, the resulting speed is higher or lower than that desired for a particular use; therefore, some means of varying the speed must be provided.

In most dc motors, the armature speed is affected by the torque. If the torque is increased, the armature speed increases. If the torque is decreased, the armature speed decreases. As previously explained, torque is proportional to the field strength and the armature current. Any change in either the field strength or the torque will cause a change of armature current and armature speed. Armature voltage and field strength may be varied by external variable resistors, as shown in Figure 1-20.

The circuits of Figure 1-20 show the use of speed controls in shunt, series and compound motors. The start resistors are made for continuous use and are used to limit the armature current. Carrying the armature current, the start resistor develops a voltage drop and lowers the voltage across the armature. As a result, the balancing counter emf is induced at a lower speed. This method gives a wide range of speeds. The motor will also develop any desired torque over its working range.

There are three major disadvantages to this speed control method: An excessive amount of power is lost in the series resistor; speed regulation is very poor because of the voltage variation across the series resistor with changes of armature current; and the start resistor must be able to dissipate large amounts of heat. For these reasons, the start resistor is used only for starting the motor.

The speed of a motor is usually controlled by varying the field current with a field rheostat. The field rheostat is connected in series with the shunt field of a shunt or compound motor, or in parallel with the series field of a series motor. If the field rheostat is adjusted to decrease the field current, the flux is also decreased. With a weaker field, a lower counter emf is induced in the armature. As a result, the armature speed increases. In contrast, if the field rheostat is adjusted to increase the field current, the flux and counter emf are increased and the armature current and speed are reduced.

This method of speed control is very efficient as far as power is concerned, and the regulation is excellent for any particular speed adjustment.

Reversing Motors

Returning to Figures 1-14B and 1-14C and the right-hand rule shown in Figure 1-15, the direction that the wire moves in the magnetic field depends upon the directions of flux and current. If either is reversed, the direction of motion reverses. If both are reversed, the relation between them is not changed, and the direction of motion does not change.

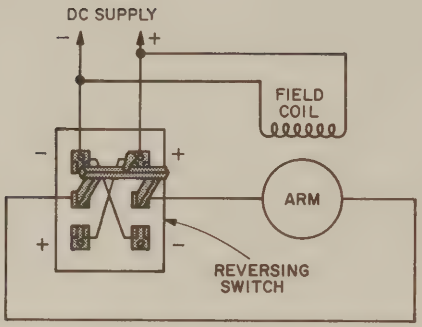


Figure 1-22

Figure 1-22 shows how to reverse a shunt motor. The FIELD COIL is connected directly across the DC SUPPLY, while the armature is connected to the DC SUPPLY through a REVERSING SWITCH. The REVERSING SWITCH is a double-pole, double-throw knife switch with six external connections. Although electrically insulated from each other, the movable blades are operated simultaneously. To complete the REVERSING SWITCH circuits, jumpers are connected from the upper left to lower right of the switch and from the upper right to lower left of the switch.

When the movable switch blade is in the upward position, there is a circuit from the −supply wire through the left-hand switch blade, through the armature from right to left and through the right-hand switch blade to the +supply line.

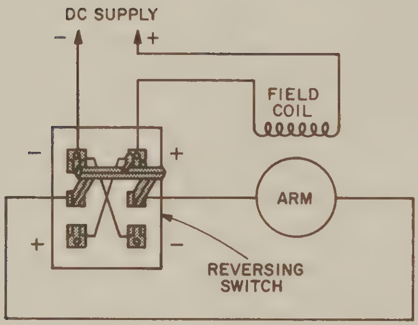


Figure 1-23

When the movable switch blade is in the downward position, the jumpers reverse the connections between the supply and the switch blades. There is a circuit from the −supply line through the right-hand switch blade, through the armature from left to right and through the left-hand blade to the +supply line. Thus, without changing the field current direction, the switch reverses the armature current direction to cause motor operation in either the forward or reverse direction.

You can reverse a series motor by connecting a reversing switch in the armature circuit as shown in Figure 1-23. Instead of connecting it in the armature circuit, the REVERSING SWITCH may be connected in the field circuit. Compound motors are also reversed by reversing the voltage across the armature.

DC GENERATOR AND MOTOR CONSTRUCTION

The construction of a dc generator or motor is shown in Figure 1-24. The magnetic field is produced by electromagnets mounted on the inside of a cylindrical steel frame or yoke. Depending on the output needs, the field flux is produced by one or more pairs of poles.

The cylindrical armature consists of the SHAFT, ARMATURE CORE, ARMATURE COILS, and COMMUTATOR. The SHAFT is held by BEARINGS in both of the end bells. Carbon or copper brushes in insulated holders are pressed firmly against the COMMUTATOR by springs. These springs keep the proper pressure on the brushes.

Although the number of armature core slots and coils varies, there are usually as many commutator segments as there are coils. However, some-

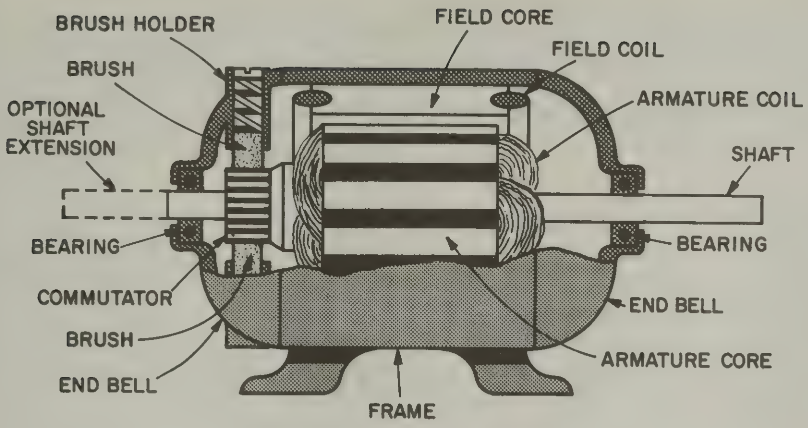


Figure 1-24

times there is one more slot and coil than there are segments. In this example, the coil is left unconnected and referred to as a dead or dummy coil. This coil balances the motor so it will not vibrate.

Eddy currents are induced in the field poles and armature cores by changes in magnetic flux as the armature rotates. With solid FIELD and ARMATURE CORE, the eddy currents are high. The resulting magnetic flux cancels part of the field flux and lowers the efficiency.

To reduce eddy currents, the FIELD and ARMATURE CORE are constructed of a stack of thin pieces of sheet iron coated with insulating varnish. This laminated construction has about the same permeability as a solid piece of iron, but the insulation reduces the eddy currents and improves the efficiency.

ARMATURE REACTION AND ITS CORRECTION

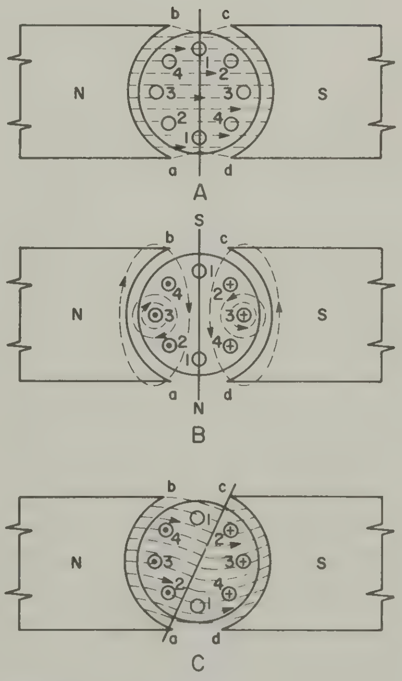


Figure 1-25

Figure 1-25A shows the cross section of a two-pole, four-coil generator or motor. Neglecting for a moment the armature current and its effects, the magnetic flux set up by the field coils extends straight across the gap from the N pole to the S pole as shown by the light, dashed lines. The magnetic flux is now evenly distributed across the pole faces.

When the motor or generator is in operation, current is in the armature coils. In Figure 1-25B, electrons flow out of the conductors near the N field pole and into the conductors near the S field pole. A dot or cross inside a small circle represents the point or tail of an arrow, respectively. The circles without a dot or cross represent the sides of the short-circuited coil.

Neglecting for a moment the field flux, and its effect, the armature current magnetizes the core so that it has an S pole at the top and an N pole at the bottom. Because it produces a flux at right angles to the field flux, the armature is said to be cross magnetized.

When the motor or generator is operating normally, these magnetic fields interact. The magnetic fields oppose each other at pole tips a and c, and attract each other at pole tips b and d. As a result, the magnetic field is distorted as shown in Figure 1-25C. The flux is now unevenly distributed across the pole faces. This interaction between the flux of the field and armature is called **ARMATURE REACTION.** It occurs in both motors and generators.

Referring to Figure 1-25A, the sides of coil 1 move parallel to the magnetic flux and have zero induction in them. They lie in what is known as the **NEUTRAL PLANE**. As used here, a plane is an imaginary surface that has length and width but no thickness. In the generator and motor, the neutral plane is defined as a plane that is at right angles to the field flux, where there is zero induction in the armature coils.

In Figure 1-25A, the vertical line through coil 1 shows the location of the neutral plane when there is no current in the armature, and the field flux is undistorted. This plane often is called the normal neutral plane. When there is current in the coils, the magnetic field is distorted as shown in Figure 1-25C. As a result, the neutral plane shifts until it is again at right angles to the field flux.

The shift of the neutral plane depends upon the armature current, which varies with the load. A light load causes a low armature current and a small neutral plane shift. Conversely, a heavy load causes a high armature current and a large neutral plane shift.

With a given field polarity and armature current direction, the direction of neutral plane shift is in the direction of rotation in a generator, and in the opposite direction of rotation in a motor. For example, if Figure 1-25C is a generator, the left-hand rule shows that the armature is turning in a clockwise direction. Shifting from the vertical position of Figure 1-25A to that of Figure 1-25C, the neutral plane moves in the direction of rotation. Conversely, if Figure 1-25C is a motor, the right-hand rule shows that the armature rotation is counterclockwise. Thus, the neutral plane moves opposite to the direction of rotation, to reach the position shown in Figure 1-25C.

For the generator shown in Figure 1-6 and the motor shown in Figure 1-18, the brushes are arranged to short-circuit the coils in which there is zero induction. Another way of saying this is that the brushes must short-circuit the coils in the neutral plane. For this reason, the neutral plane sometimes is called the **COMMUTATING PLANE**.

Brush Sparking

Brush sparking occurs if the conductor-induced voltage, self-induced voltage, or mutual-induced voltage is too high.

The voltage induced in a coil depends upon the relative positions of the coil sides and the magnetic pole. Thus, the induced emf in the coil at the moment of commutation changes when you move the brushes one way or the other with respect to the pole pieces. Known as the "armature reactance voltage," the emf or self and mutual induction is not affected by the positions of the conductors and magnetic poles. It is produced by the current change in a coil as a result of commutation. Although the armature reactance voltage may be kept low, it cannot be completely eliminated.

Up to now, it has been assumed that the coil undergoing commutation is in such a position that it has zero induced voltage in it. However, when the coil is commutated, the resulting armature reactance voltage may be high enough to cause sparking.

One method of reducing commutation sparking is to shift the brushes until the coil being commutated is in the fringe of the main magnetic field. The resulting induced emf opposes the reactance voltage and reduces sparking. With no load, the brushes of a generator are shifted in the direction of rotation, and those of a motor are shifted in the direction opposite to rotation. However, as the load is applied, the armature current increases and the neutral plane shifts, as shown in Figure 1-25C. This reduces the fringe field strength and lowers the induced voltage. Simultaneously, the higher armature current causes an increase of reactance voltage. The increasing load finally reaches a point where the reactance voltage again exceeds the fringe-generated emf enough to cause sparking. Thus, the degree of brush shifting depends on the load, and a change of load demands a different brush position.

Brush shifting is used in some generators and motors to reduce commutation sparking. But this method is not always satisfactory. It has a rather limited load range, and it produces a demagnetizing effect on the field flux.

Commutating Poles

For best results, the brushes should be close to the commutating plane. But when there is a change of load, there is a corresponding change of armature reaction. As a result, the commutating plane shifts, and a problem to keep the brushes in the most desirable position develops.

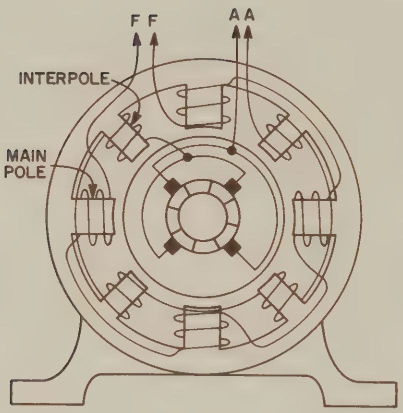


Figure 1-26

Commutation is improved by shifting the brushes to bring the coil under commutation into the fringe of the main magnetic field. The results are the same if you leave the brushes in the normal neutral plane and move the magnetic field back to them. This is done by placing small auxiliary poles midway between the main poles as shown in Figure 1-26. Such auxiliary poles are known as **INTERPOLES** or **COMMUTATING POLES**.

The windings of commutating poles are connected in series with the load, and are arranged to produce magnetic poles, as shown in Figure 1-26. Because the commutating pole windings carry the load current, the magnetic fields they produce are always proportional to the armature current. They also reduce the shift of the neutral plane with load variations. Thus, there is sparkless commutation at all loads. As a result, little or no brush shifting is needed and the brushes can be permanently mounted in one position.

REGULATION

The **REGULATION** of a generator with various loads is the ratio of the difference between the no-load and rated full-load voltages to the rated full-load voltage. Usually this ratio is multiplied by 100 to give a percentage:

$$\text{Percent Regulation} = \frac{E_N - E_F}{E_F} \times 100 \qquad (1)$$

where:

E_N is the no-load voltage, and
E_F is the rated full-load voltage.

Assume that the no-load voltage is 110 volts and the rated full-load voltage is 100 volts. The percentage of regulation is:

$$\begin{aligned}\text{Percent Regulation} &= \frac{E_N - E_F}{E_F} \times 100 \\ &= \frac{110 - 100}{100} \times 100 \\ &= \frac{10}{100} \times 100 = 10\%.\end{aligned}$$

In most applications, a low regulation percentage is desirable. It indicates that a generator has a rated full-load voltage very close to the no-load voltage.

For "constant-speed" dc motors, the regulation is the ratio of the difference between the no-load and rated full-load speeds to the full-load speed under rated full-load conditions. Usually this ratio is multiplied by 100 to give a percentage:

$$\text{Percent Regulation} = \frac{S_N - S_R}{S_R} \times 100 \tag{2}$$

where:

S_N is the no-load speed in revolutions per minute (rpm), and
S_R is the rated full-load speed in rpm.

Assume that the no-load speed of a dc motor is 3600 rpm and the rated full-load speed is 3500 rpm. The percentage of regulation is:

$$\text{Percent Regulation} = \frac{S_N - S_R}{S_R} \times 100 = \frac{3600 - 3500}{3500} \times 100$$

$$= \frac{100}{3500} \times 100 = 2.86\%.$$

Speed regulation is a measurement of the ability of a motor to maintain its speed when a load is applied. A low-speed regulation percentage is also desired.

EFFICIENCY

A certain part of the energy delivered to a motor or generator is lost within it in the form of heat. Not only is the energy wasted, it also heats up the motor or generator and limits its output. If the energy loss becomes excessive, the resulting temperature rise may break down the insulation.

The losses developed in a motor or generator may be summarized as follows:

Copper Losses—I^2R or power losses caused by the current in the armature and in the field windings, the brushes, the commutator, and the brush-to-commutator contact resistance.

Iron Losses—Power losses caused by eddy currents and hysteresis in the armature core and poles.

Friction Losses—Power losses caused by the friction of the bearings and brushes.

The **EFFICIENCY** of a generator or motor is the ratio of the output to the input. To obtain a percentage, the ratio is multiplied by 100:

$$\text{Percent Efficiency} = \frac{\text{output}}{\text{input}} \times 100. \tag{3}$$

The efficiency equation may also be written:

$$\text{Percent Efficiency} \times \frac{\text{input} - \text{losses}}{\text{input}} \times 100. \tag{4}$$

To use either of these equations, the output and input values must be expressed in the same terms, either electrical or mechanical. The following example shows the steps to follow when one quantity is given in mechanical terms and the other is given in electrical terms.

Assume that you have a motor that develops a full rated output of 1.5 horsepower and draws 5.74 amperes at 250 volts. What is the efficiency of this motor?

Step 1. Find the number of watts corresponding to 1.5 horsepower (1 HP = 746W):

$$1.5 \times 746 = 1119 \text{ watts.}$$

Step 2. Find the input power:

$$P = IE = 5.74 \times 250 = 1435 \text{ watts.}$$

Step 3. Find the efficiency:

$$\text{Efficiency} = \frac{1119}{1435} \times 100 = 77.9\%.$$

Most power devices have a definite power rating. Determined by the manufacturer, this rating gives the power the machine can safely or efficiently deliver under given conditions. For generators, the power rating is in watts or kilowatts. For motors, the power rating is in mechanical horsepower.

SPECIAL DC MOTORS AND GENERATORS

Besides the "conventional" dc motors and generators there are special dc motors and generators such as the dynamotor, printed-circuit motor and brushless motor.

Dynamotors

If the required power differs in frequency or voltage from the supplied power, a motor-generator set may be used. This motor-generator set consists of a motor and generator mounted on a common base with their shafts coupled together. The motor works on the supplied power and turns the generator. The generator works as a separate electric unit to produce the required kind of power.

To achieve higher efficiency, the motor and generator may be combined into a single unit with one frame called a **DYNAMOTOR.** Units of this type are used to supply operating voltages for transmitters and receivers. The frame carries the conventional field circuit and poles, but the armature carries two independent sets of windings and commutators.

The field and one armature winding can operate as a motor on the available low-voltage dc. The other armature winding generates the desired dc output. Conventional dynamotors operate on 6, 12, 24, or 110 volt dc circuits, and produce a variety of dc outputs, usually higher than the supply voltage.

Because of the way the armature coils are wound and connected, electrons flow in opposite directions in the motor and generator coil sides in the same slots. As a result, the armature reaction is canceled, there is no neutral plane shift, and sparking is reduced.

Because of the cancellation of armature reaction, the total losses in the dynamotor are less than in a motor-generator set; therefore, the efficiency is higher. Because the field flux does not have to overcome the armature reaction, a lighter field winding and core can be used. The dynamotor can be more compact and weigh less than a motor-generator set.

Major disadvantages of a dynamotor are: (1) the output voltage cannot be varied except by varying the input voltage, and (2) the voltage regulation is not as good as that of a motor-generator set.

Printed-Circuit Motors

A recent development in the motor industry is the **PRINTED-CIRCUIT MOTOR.** The name comes from the fact that such a motor uses a printed-circuit armature. Printed-circuit motors are used extensively in servomechanism systems. Because the first printed-circuit motors supplied only small amounts of torque they were limited in use. This is no longer true. Printed-circuit motors are now capable of producing large amounts of torque and are being widely used in a variety of applications.

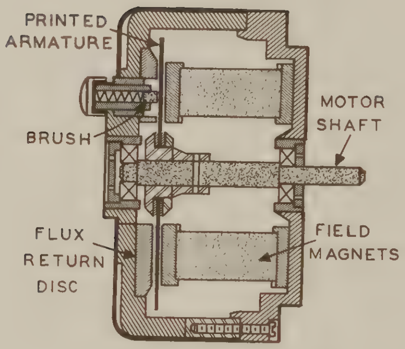


Figure 1-27

A cutaway view of a printed-circuit motor is shown in Figure 1-27. The basic principle of operation in this type of motor is similar to that of a conventional motor. The main difference is in the armature assembly. As shown in Figure 1-27, the armature of a printed-circuit motor is a thin disc mounted on a shaft. In Figure 1-27, the PRINTED ARMATURE disc is shown from the side. The diameter of this disc may range anywhere from about $3^1/_2$ inches to almost 50 inches, depending on the rating of the motor.

Front views of the Printed Armature disc are shown in Figure 1-28. You can get a better idea of how the Printed Armature disc is constructed in this view. The Printed Armature disc is made of a nonconductive material, with flat, ribbon-like copper conductors printed on both sides. The light areas of the armature shown in Figure 1-28A are the copper conductors. The dark lines between the conductors are the nonconductive disc material. The conductors are the windings of the armature and form the armature loops. The reverse side of the armature is similar to the side shown.

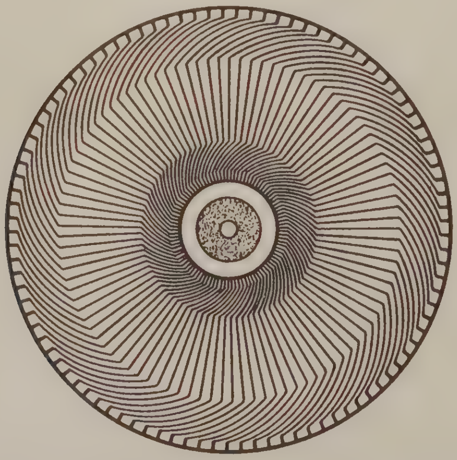

A

Figure 1-28

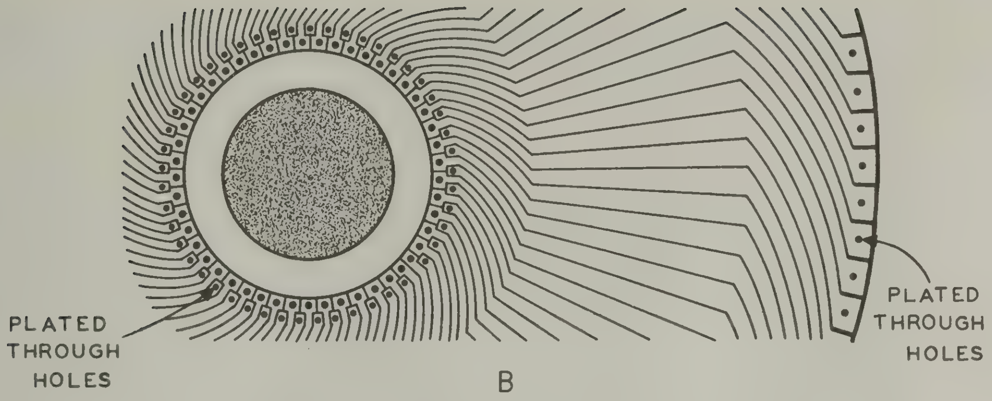
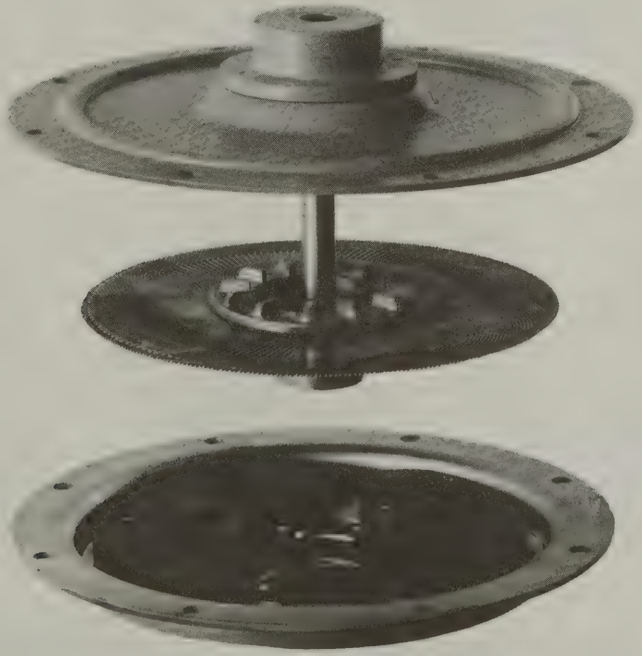


Figure 1-28

Connections between the sides of the armature are made by PLATED THROUGH HOLES shown at both ends of the windings in Figure 1-28B. A hole is drilled through the conductor and disc material to the corresponding part of a conductor on the other side of the Printed Armature disc. The hole is then plated with a conductive material and the two conductors on opposite sides of the Printed Armature disc are electrically connected to form a loop.



This "pancake" printed-circuit motor has 8 poles and 4 brushes. This type of motor is rated at $^1/_{30}$, $^1/_{13}$, and $^1/_8$ HP at between 2000 and 2600 rpm.
Courtesy Photocircuits Division, Kollmorger Corporation

There are usually about 100 to 200 armature conductors in a printed-circuit motor, depending upon the motor's rating. Just as in a conventional motor, the more armature conductors a printed-circuit motor has, the more power it can develop.

Notice the physical position of the BRUSH in Figure 1-27. While only one brush is visible in this cutaway view, there are other brushes spaced at intervals around the motor case. The brushes ride directly on the armature conductors to form sliding contacts between the conductor loops and the armature voltage source. The brushes touch only a certain group of conductor strips at any given point of armature rotation, so that there is a commutator action without the need for a separate commutator. Because there are so many armature conductors, the printed-circuit motor operation is very smooth.

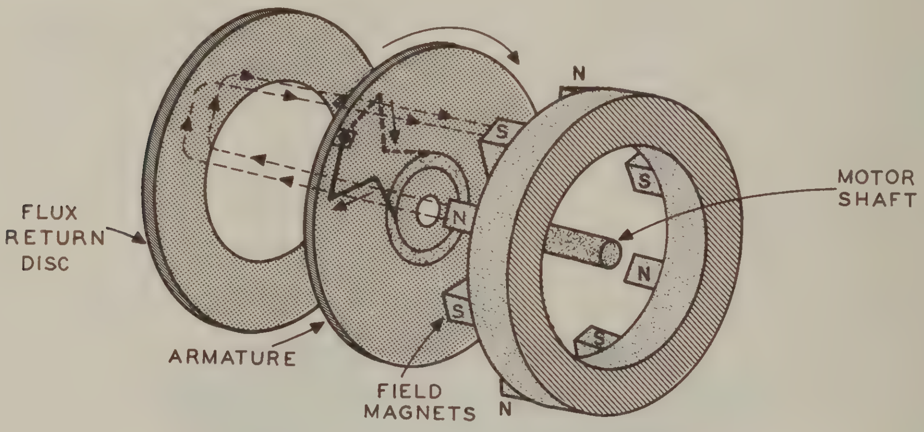


Figure 1-29

Figure 1-29 is an exploded view of a printed-circuit motor. The motor has been simplified to show the basic action. Only one armature loop is shown in this figure. The loop extends from the center to the outer edge on the front of the ARMATURE disc, through the plated hole, and from the outer edge to the center on the back of the ARMATURE disc. The conductor on the front of the ARMATURE disc is represented by a solid line, while the conductor on the backside of the ARMATURE disc is represented by a dashed line. Although they are not shown in this figure, a set of brushes connects the ends of the loop to an external voltage source.

The field is supplied by the FIELD MAGNETS spaced around the frame. In a conventional dc motor the lines of force pass from an N pole on one side of the loop to an S pole on the opposite side of the loop. But in the printed-circuit motor, the magnetic path is a little different. The lines of force pass from an N pole through a FLUX RETURN DISC and back to an

S pole mounted beside the N pole on the frame. This flux path is shown by the dashed-line arrows in Figure 1-29.

The FLUX RETURN DISC is a good magnetic conductor, and therefore, it acts to "steer" the lines of force between the set of adjacent magnetic poles as shown in Figure 1-29. The ARMATURE is mounted between the poles and FLUX RETURN DISC, in the path of the magnetic lines. The lines of force from the N pole cut the front conductor of the ARMATURE disc in one direction, pass through the FLUX RETURN DISC and cut the back conductor of the ARMATURE disc in the opposite direction as they return to the S pole. Thus, the field effect is basically the same for the two sides of the loop in a printed-circuit motor as it is for the two sides of the loop in a conventional motor, although the physical arrangement is different.

As previously explained, the brushes form a sliding contact between the voltage source and the armature conductors. Current through an armature conductor causes a magnetic field around the conductor. The small arrows near the conductors show the directions of current in the front and back conductors of the loop. By applying the right-hand rule, you will find that the ARMATURE tends to turn in a clockwise direction.

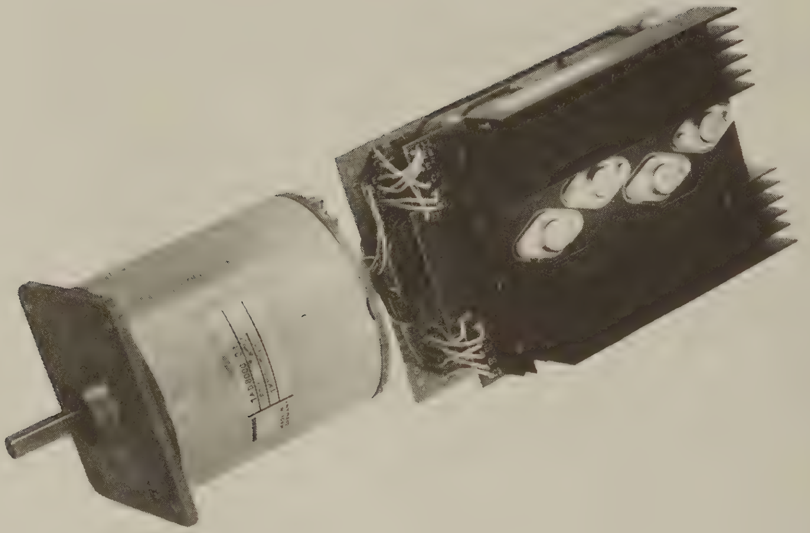
We have described the torque developed by only one armature winding. The armature has many of these windings and they are arranged so that all torques add together to produce a large output torque. For example, a motor with an axial length of 1.6 inches and a diameter of 11 inches produces 1.25 horsepower. Compare this size and power to other motors which you have seen and you will appreciate the size advantage.

A printed-circuit motor also has other advantages. As a result of the light weight of the armature for a given power rating, certain types of printed-circuit motors are capable of starting and stopping 300 times a second. This makes printed-circuit motors ideal where fast response is necessary.

Printed-circuit windings have very low resistance, usually much less than 1 ohm. Thus, a relatively low operating voltage will produce the high current required to obtain a dense armature field. For instance, some of the smaller printed-circuit motors operate on a 6 volt supply. This feature makes printed-circuit motors ideal for operation with power transistors which are primarily low voltage devices.

Brushless DC Motors

There are many places where dc motors are needed but where brush sparking cannot be tolerated. Sparking causes interference to radio and TV



This variable speed brushless dc motor is rated at 1260 to 1540 rpm and 28 oz-in of torque. Behind the motor is the solid state control circuitry that establishes these ratings. A similar motor with a more sophisticated control circuit also provides a rated 28 oz-in of torque over an adjustable range of 300 to 6000 rpm.

Courtesy Siemens Corporation

reception, and causes ozone to be formed from oxygen. Brushless dc motors are often used in satellites, buildings housing radio communication equipment and in hospital operating rooms. Some brushless dc motors, called "stepper motors," are designed to make only partial revolutions when dc pulses are applied to them.

Continuously rotating brushless dc motors often have permanent magnets for the rotating part (called a rotor). In some motors, two square wave or trapezoidal waveforms that have 90° phase shift between them are applied one each to a set of field windings, which causes a rotating field to appear in the motor. This causes the permanent magnet rotor to revolve. Many of these motors use "Hall effect" devices to sense the position of the permanent magnet rotating part so as to trigger the switching circuitry.

MAINTENANCE OF DC MOTORS AND GENERATORS

Preventive maintenance helps to ensure long life in motors and generators. By preventive maintenance, we mean the periodic checking of a device to detect trouble before it becomes severe.

Sparking can be caused by a dirty commutator, overloading, not enough brush tension, worn brushes or open armature coils. The commutator in a motor or generator receives more wear than any other part. For this reason it should be examined frequently.

The commutator can be cleaned and smoothed by using a piece of number 00 sandpaper while the motor is running. The next step is to place a few drops of mineral oil on the sandpaper and polish the commutator. Do not use too much oil and never use emery cloth. Emery cloth contains metallic particles which will cause a coil to be permanently short-circuited.

Mica is an insulating material which is used between commutator segments. As a commutator wears it becomes rough. This roughness is sometimes caused by the mica protruding past the surface of the commutator, as shown in Figure 1-30A. This prevents a smooth contact between the brushes and the commutator segments. By undercutting the mica as shown in Figure 1-30B, good contact is once again obtained between the brush and commutator. If the commutator is badly nicked and cut, it should be turned smooth on a lathe.

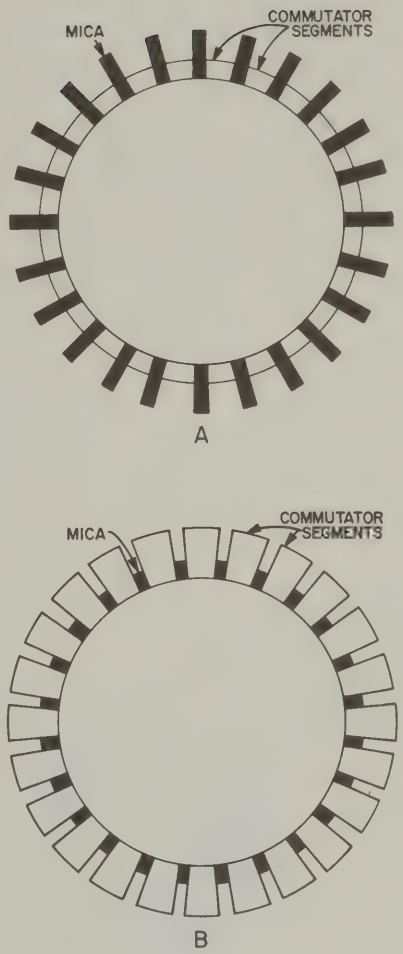


Figure 1-30

Most of the brush trouble is caused by poor brush tension, worn brushes and brushes which are out of the neutral plane. The spring tension must be correct for good electrical contact between the brush and commutator. If the tension is too loose, the brush will bounce. This condition will cause brush arcing, and may cause the commutator to become rough. If the tension is too tight, it will increase brush wear. Proper operation calls for proper adjustment of the tension to the point where the brush just stops bouncing.

Proper fitting of the brushes in their holders is also important. If the brush does not move freely in its holder, the holder should be cleaned. If a brush is to be replaced because of wear, an exact replacement must be used. The brush should be shaped so that its entire face contacts the commutator. If the entire brush face does not contact the commutator, the brush will spark because the surface area is not large enough to carry the proper current.

When a commutator is turned down with a lathe, the brush may have to be reshaped to fit the new size of the commutator. To reshape the brush, place a strip of very fine sandpaper, narrower than the commutator length but wider than the brush width, between the brush and commutator. Then, turn the armature in the normal rotating direction.

A voltmeter can be used in the simple test arrangement of Figure 1-31 to find shorts or opens in armature windings. In an armature, the number of turns

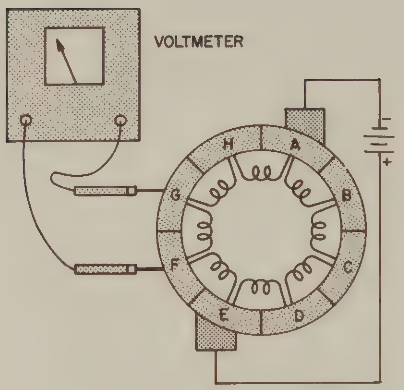


Figure 1-31

between adjacent segments is equal, and the number of coils between the segments on which the brushes rest is equal. Thus, the voltage across each segment should also be equal. Using a dc source and turning the armature by hand, if the coil between segments F and G in Figure 1-31 is shorted, there will be no voltage across it and the meter will read zero. If this coil is open, the meter will read the full dc supply voltage.

If trouble is indicated check the connections between the coils and segments. Poor solder joints may give a false indication of an open coil. If the mica in the commutator was undercut, check to see that no foreign metal is shorting two commutator segments together. This gives a false indication of a short.

An unwanted current path from the armature to the motor frame, known as grounding, can be caused by a poor insulation. To test for such grounding, place one ohmmeter test lead on the motor frame. Place the other ohmmeter test lead on different segments of the commutator. If you get a much lower resistance reading at one segment than at others the chances are that the insulation of the coil connected to that segment is defective.

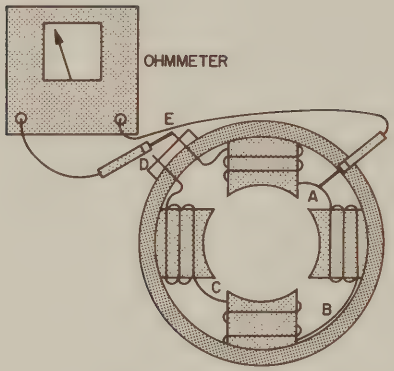


Figure 1-32

Field coils can be tested with an ohmmeter, as shown in Figure 1-32. If you place the ohmmeter test leads on points E and D of Figure 1-32, and the meter reads some definite resistance value, the circuit is completed. If the reading is infinite, the circuit is open. The next step is a continuity test to find where the open exists. With one ohmmeter test lead on point E as shown, the other ohmmeter test lead should be placed on point A, then point B, then point C. If the ohmmeter indicates continuity between point E and point A, but an open circuit between points E and B, there is a break in the circuit between A and B.

Another source of trouble in a motor or generator is the bearings. The bearings on many motors and generators require periodic lubrication. The lubricant is usually inserted through an oil or grease cup. Overlubrication can be harmful. For example, the space between the motor or generator end housing and the armature generally should not be filled with grease. Grease on the commutator can reduce the brush contact area.

Bearing overheating can cause the condition known as freezing, where the rotor shaft and the bearing lock together. One cause of bearing overheating is improper lubrication. If a bearing overheats, the motor or generator should be slowed down, but not stopped, and oil or grease applied. This will prevent freezing of the shaft. Bearings that wear out must be replaced.

The following Practice Exercise questions cover the subjects which you have just studied. They are:

- DC MOTOR OPERATION
  - SINGLE-LOOP MOTOR
  - TORQUE
  - COUNTER EMF
  - MULTI-LOOP MOTOR
  - MOTOR TYPES
  - STARTING DC MOTORS
  - MOTOR SPEED CONTROL
  - REVERSING MOTORS
- DC GENERATOR AND MOTOR CONSTRUCTION
- ARMATURE REACTION AND ITS CORRECTION
  - BRUSH SPARKING
  - COMMUTATING POLES
- REGULATION
- EFFICIENCY
- SPECIAL DC MOTORS AND GENERATORS
  - DYNAMOTORS
  - PRINTED-CIRCUIT MOTORS
  - BRUSHLESS DC MOTORS
- MAINTENANCE OF DC MOTORS AND GENERATORS

11. In using the right-hand rule for motors, the thumb shows the direction of (a) current, (b) magnetic flux, (c) wire movement.

12. In using the right-hand rule for motors, the forefinger shows the direction of (a) current, (b) magnetic flux, (c) wire movement.

13. What is the purpose of the brushes and commutator segments of the simple motor shown in Figure 1-17?

14. In a motor, counter emf opposes the supply voltage. True or False?

15. If the speed of a motor is increased, the motor develops a (a) smaller counter emf, (b) larger counter emf.

16. If counter emf increases, armature current (a) decreases, (b) increases, (c) remains the same.

17. The torques produced in the motor of Figure 1-18 by the armature windings in slots B and F tend to turn the armature in (a) the same direction, (b) opposite directions.

18. Which type of motor is known as a constant-speed motor?

19. If the load is removed from a series motor, the motor can speed up until it destroys itself. True or False?

20. In starting a shunt-wound motor, the resistance in series with the armature should be (a) maximum, (b) minimum.

21. Speed control of a motor is usually obtained by varying the current through the field winding. True or False?

22. The direction of rotation of a dc shunt-wound motor armature can be reversed by reversing the polarity of the field coil supply. True or False?

23. The interaction between the flux in the field and armature is called (a) cross magnetization, (b) armature reaction.

24. There is maximum induction in the armature coils which lie in the neutral plane of a motor. True or False?

25. The neutral plane of a motor or generator shifts as the load on the motor or generator changes. True or False?

26. For a minimum of sparking, the brushes of a generator or motor should always be out of the neutral plane. True or False?

27. In a generator, the no-load voltage is 250 volts and the full-load voltage is 230 volts. What is the percentage of regulation?

28. A motor rated at 1/2 horsepower draws 3.88 amperes at 120 volts. What is the efficiency of the motor?

3.88
12
776
388
465.6

373

SUMMARY

All generators operate on the principle of electromagnetic induction. In this process, voltage is induced in a wire cut by a magnetic field. Generators differ mainly in the number of loops and segments used. By increasing the number of equally spaced loops and segments, the induction and output voltage are increased. The output voltage is also smoother or more nearly constant. The multi-loop generator therefore provides more efficient operation. There are three types of dc generators: shunt, series and compound.

Motors change electrical energy to mechanical energy. They resemble generators in structure, but differ in their method of operation. The three types of motors are shunt, series and compound, depending on the way their field winding is connected to the armature.

Torque and speed are very important in many applications of motors. Certain applications require high torque and variable speed. Others require constant speed. Because of their variable speed, dc motors are used in such applications as servomechanisms and variable speed machinery. Because of their high torque, dc motors are also used to drive the heavy loads encountered in electric buses, trucks and trains.

A combined unit of motor and generator is called a dynamotor. In this unit, the motor is operated on a low dc voltage, and the generator usually delivers a high dc voltage.

Failure of a motor in industry may cause a shutdown of many dependent departments. Motor repairs must be made promptly. It is better to keep all motors and generators in top working order at all times through preventive maintenance. This includes cleaning, adjusting, and lubricating all moving parts, and testing armatures and field coils.

PART 2—AC MOTORS AND GENERATORS

AC motors and generators play a very important role in the home and industry. You probably encounter ac motors in your daily routine, as they are part of most home appliances, and they power most of the equipment in industrial plants. The power delivered to most homes, factories and places of business is generated by power companies. Some industries generate their own ac power, or at least maintain emergency standby generators.

AC GENERATOR OPERATION

Because an ac generator develops alternating current, it is commonly referred to as an **ALTERNATOR**. Alternators operate as ac generators and are often called **SYNCHRONOUS GENERATORS**. Most power companies supply 60 Hz ac power. However, alternators can be designed to produce 400 Hz ac power, or power at other frequencies that are desirable for a given application. The voltages and current ratings of alternators also differ from one application to another; therefore, alternators are constructed in a variety of forms.

A Simple Alternator

Alternating current continually changes value and periodically reverses its direction. Figure 2-1 shows a basic method of producing such a current. While alternators in practical use are more complex, they do operate on the same basic principles.

The simple alternator of Figure 2-1 includes a magnetic field set up between the two poles of a permanent magnet, and a wire loop mounted on, but electrically insulated from, a rotating shaft. To complete the electric path, each end of the loop is connected to a copper collector (or slip ring). The collectors are also mounted on, but electrically insulated from, the shaft. The complete assembly of loop, collector rings and shaft is known as the armature. Pressing against the rings, carbon or copper brushes make sliding connections between the loop and the external circuit.

Inside the alternator, the electric circuit is from one collector ring, back along one side of the loop, across the back, forward along the other side of the loop to the other collector ring. The brushes and external load complete the circuit. Although the loop is rotated, the loop connections to the external circuit do not change because of the collector ring construction. The collector ring connected to side A of the loop always contacts brush 1, and the collector ring connected to side B always contacts brush 2, regardless of the position of the loop.

Let's look at the collector rings more closely. Because the collector rings are continuous they cannot switch the loop connections as does the commutator in a dc generator. This is the main difference between most ac and dc generators.

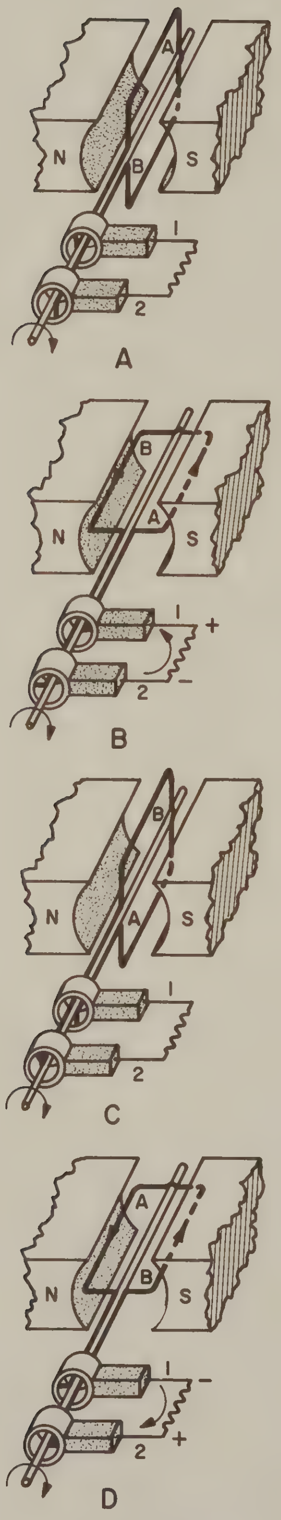


Figure 2-1

Electromagnetic induction depends on the relative motion of a conductor in a magnetic field. In Figure 2-1, assume that the armature rotates at a constant speed in a clockwise direction as shown by the curved arrow near the shaft.

When the loop is in the position shown in Figure 2-1A, loop sides A and B are moving parallel to the lines of force; and no voltage is induced in the loop. With no induced voltage in the loop sides, brushes 1 and 2 are at the same potential, and there is no current in the external circuit. The wires across the front and the back of the loop and the wires from the loop to the collector rings are outside the magnetic field, and have no voltage induced in them.

As the armature turns, loop side A moves to the right and down past the S pole, while side B moves to the left and up past the N pole. When the armature is in the position shown in Figure 2-1B, the loop sides move directly across the flux, and maximum voltage is induced in them. Applying the three-finger, left-hand rule, current is from the front of the loop to the back on side A and from the back of the loop to the front on side B. Tracing the circuit from one collector ring to the other, you will find that both voltages act in the same direction. The voltage between the brushes is the sum of the voltages induced in the sides of the loop, and brush 1 is positive with respect to brush 2. In the external circuit, electrons leave brush 2 and flow through the load to brush 1.

Another quarter turn and the loop is in the position shown in Figure 2-1C. As in Figure 2-1A, the loop sides are now moving parallel to the flux lines, and no voltage is induced in the loop.

As the loop moves to the position shown in Figure 2-1D, current is from front to back along side B and from the back of the loop to the front on side A. This is just the opposite of Figure 2-1B, so that brush 1 is negative and brush 2 is positive. In the external circuit, electrons leave brush 1 and flow through the load to brush 2. Another quarter turn brings the armature back to its original position, where the sides move parallel to the flux lines. As the loop is turned, the current in the load periodically reverses direction; therefore, it is an alternating current. As previously mentioned, the device shown in Figure 2-1 is called an alternator (or ac generator) because it generates an alternating voltage.

Four loop positions are shown in Figure 2-1, which represent the two positions of maximum cutting and the two positions of zero cutting. As the loop rotates, the degree of cutting increases from zero (Figure 2-1A) to maximum (Figure 2-1B), and the amount of voltage induced in the loop increases accordingly. As the loop continues its clockwise rotation, the degree of cutting decreases from maximum to zero (Figure 2-1C), and the induced voltage decreases with it.

The same holds true for the second half of the rotation, from the position shown in Figure 2-1C through the position shown in Figure 2-1D and back to

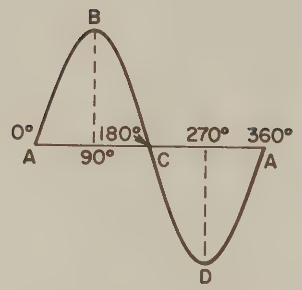


Figure
2-2

the position shown in Figure 2-1A. The degree of cutting and the amount of induced voltage increase from zero (Figure 2-1C) to maximum (Figure 2-1D), and then decrease to zero (Figure 2-1A).

A graph of the alternator output is shown in Figure 2-2. The curve shows the polarity of brush 1 with respect to brush 2, and the magnitude of the emf generated during one complete turn of the armature. The horizontal line through the center of the curve represents zero voltage. All points on the voltage curve above the line represent positive voltages, while those points below the line represent negative voltages. The letters near the curve correspond to the armature positions shown in Figure 2-1.

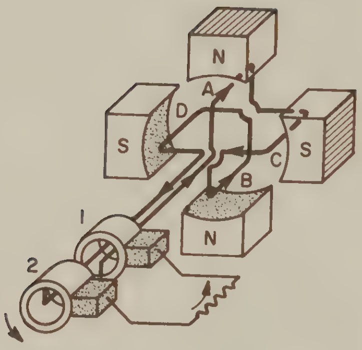


Figure
2-3

A Four-Pole Alternator

To generate practical amounts of power, most alternators have magnetic fields with more than two poles, and armatures with more than one loop of wire. In the four-pole alternator of Figure 2-3, the armature winding has two loops, each made up of a single turn or a coil of many turns.

Figure 2-4 shows the pole arrangement of Figure 2-3. Notice the direction of flux lines. When a loop side passes directly in front of a pole, it crosses a maximum number of flux lines. When a loop side is exactly midway between an N and S pole, it is traveling parallel to the flux lines and does not cut any flux lines.

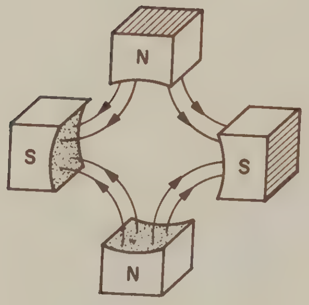


Figure
2-4

Assume that the armature rotates counterclockwise at a constant speed. When the armature is in the position shown in Figure 2-3, the conductors cut directly across the magnetic flux and a maximum emf is induced in the loop sides. Loop sides A and B are adjacent to the N poles. Using the three-finger, left-hand rule, we see that current is from the front of loop sides A and B to the back. Loop sides C and D are adjacent to the S poles. Current is from the back to the front of the loop in sides C and D. Tracing the armature circuit from one collector ring to the other, the induced emfs are all in the same direction (series-aiding). The voltage between the collector rings is the sum of all the voltages, and collector ring 1 is positive with respect to collector ring 2.

Rotation of the armature through one-eighth of a revolution, or 45°, brings the coil sides midway between the poles. At this point, the loop sides move parallel with the flux lines, and there is no induced voltage in the loops. Another one-eighth turn brings the loop sides directly opposite the magnet poles and maximum voltage is induced in the loops. However, the loop sides that were adjacent to the N poles are now adjacent to the S poles, and the induction in them is reversed. Likewise, the induction is reversed in the loop sides that were adjacent to the S poles but are now adjacent to the N poles. As a result of the reversed induction, collector ring 1 is now negative and collector ring 2 positive.

An additional 45° turn brings the loop sides to the position of zero induction. The next 45° turn brings the loop sides to the position directly across from a magnet pole. In four 45° movements, the coil side that was at the top has moved to the bottom. It is again adjacent to the N pole and the direction of induction is toward the rear of the loop side. Electrically, the conditions are the same as when the movement started. An electric cycle of 360° is completed for each half turn of the armature of a four-pole alternator.

The second half turn of the armature is the same as the first, and another electric cycle of 360° is completed. Thus, one complete mechanical revolution of the armature produces two complete electric cycles. There are two positive peaks and two negative peaks, or FOUR MAXIMUM VALUES FOR EACH REVOLUTION in a four-pole alternator.

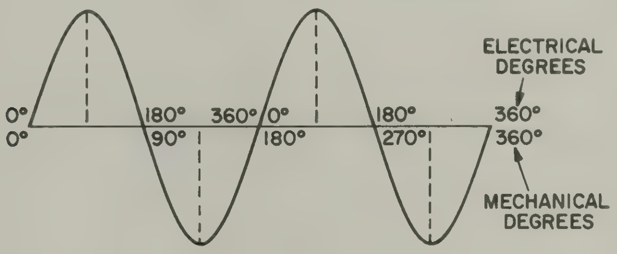


Figure 2-5

The output of the alternator shown in Figure 2-3 is represented by the curve of Figure 2-5. This curve shows the polarity of collector ring 2 with respect to collector ring 1, and the magnitude of the emf produced during one complete revolution of the armature. Mechanical degrees are shown below the zero-voltage line, and electrical degrees are shown above the zero-voltage line. Comparing this curve with that of Figure 2-2 shows the effect of doubling the number of poles in an alternator.

Alternator Frequency

The number of cycles per second produced by an alternator is called its frequency (f), expressed in hertz (Hz). Older units of frequency, cycles per second, or cps, may still be in use. With respect to the alternators of Figures 2-1 and 2-3, the two-pole alternator produces one electric cycle per armature revolution, and the four-pole alternator produces two electrical cycles per armature revolution. Thus, the induced voltage passes through one cycle when the conductor is cut by the flux of one pair of poles. For an alternator having P poles, the cycles per revolution equals P ÷ 2.

Frequency refers to the number of cycles per second, while mechanical rotation usually is measured in revolutions per minute (rpm). The armature speed must be divided by 60 to determine the speed in revolutions per second.

The relationship between the alternator speed, number of poles and frequency is written as:

$$f = \frac{P}{2} \times \frac{\text{rpm}}{60} = \frac{P \times \text{rpm}}{120} \tag{5}$$

where:

f is the frequency in hertz (or cycles per second),
P is the total number of poles, and
rpm is the armature speed in revolutions per minute.

To show the use of the preceding equation, assume that the armature shown in Figure 2-1 rotates at a speed of 3600 rpm. Placing the known values into the equation gives:

$$\begin{aligned} f &= \frac{P \times \text{rpm}}{120} \\ &= \frac{2 \times 3600}{120} \\ &= \frac{7200}{120} \\ &= 60 \text{ Hz (hertz).} \end{aligned}$$

If the speed of the alternator of Figure 2-3 is 3600 rpm, the frequency is:

$$\begin{aligned} f &= \frac{P \times \text{rpm}}{120} \\ &= \frac{4 \times 3600}{120} \\ &= \frac{14{,}400}{120} \\ &= 120 \text{ Hz.} \end{aligned}$$

As in all equations, the terms can be rearranged for greatest convenience as shown below:

$$P = \frac{120f}{rpm} \tag{6}$$

$$\text{or } rpm = \frac{120f}{P} \tag{7}$$

To generate 400-Hz current at low speeds, the number of poles is increased as was done in Figure 2-3. For example, to generate 400 Hz ac at an armature speed of 300 revolutions per minute, the alternator must have:

$$\begin{aligned} P &= \frac{120f}{rpm} \\ &= \frac{120 \times 400}{300} \\ &= \frac{48{,}000}{300} \\ &= 160 \text{ poles.} \end{aligned}$$

It is impractical to generate very high frequencies by means of rotating alternators. For example, to generate a transmitter frequency of 108 MHz, at an armature speed of 5000 revolutions per minute, the alternator must have:

$$\begin{aligned} P &= \frac{120f}{rpm} \\ &= \frac{120 \times 108{,}000{,}000}{5000} \\ &= \frac{12{,}960{,}000{,}000}{5000} \\ &= 2{,}592{,}000 \text{ poles.} \end{aligned}$$

A practical way to generate high frequencies is to use an electronic oscillator. Mechanical alternators are limited to lower frequency applications.

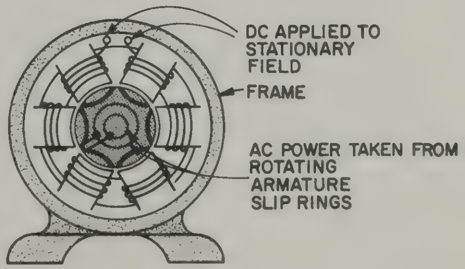

DC APPLIED TO STATIONARY FIELD
FRAME
AC POWER TAKEN FROM ROTATING ARMATURE SLIP RINGS

Figure 2-6

Alternator Construction

One general type of alternator construction is shown in Figure 2-6. The magnetic field is produced by electromagnets mounted on the inside of a cylindrical iron frame or yoke. A cylindrical armature turns inside the poles and is held by bearings mounted in housings attached at both ends of the yoke. The armature core and the field poles are laminated like a transformer core to reduce the eddy currents caused by the changing armature current.

Each field pole is wound with many turns of small wire made of a material that is easily magnetized. Adjacent poles must have opposite polarities as shown in Figure 2-4. The coils are connected in series so that when the current is through the windings, the desired polarities are obtained. For proper operation, the magnetic polarities must not change; therefore, the windings are connected to a rippleless direct current, called the EXCITING current.

The exciting current source is usually a small dc generator or a synchronous polyphase alternator (whose output is rectified into dc with a small ripple). These sources, because of their use, are called exciters. There are also static exciters which contain no moving parts. The static exciters contain transformers and rectifiers and sometimes regulators, to provide a constant dc exciting voltage. The alternator can also be SEPARATELY EXCITED. For convenience, the exciter usually is mechanically connected to the alternator shaft. In some alternators, the exciter may be driven by a separate motor or engine, depending on the needs of the installation. Some small alternators may use a storage battery as a source for the excitation current.

Another way to obtain field current is to wind another set of windings on the armature and add commutator segments to the alternator. What we really have then is a small dc generator wound on the same frame as the alternator. The output of the dc generator is then used to supply field current for the alternator. Remember, once a generator has been run, a small amount of magnetism remains in the field poles. The magnetic field is initially small, and builds up in value as the generator speed increases. With this arrangement an alternator is said to be SELF-EXCITED.

The armature windings are placed in slots that run from one end of the core to the other. The coils are connected in series so that all of the induced voltages are series-aiding. Connections to the collector (or slip) rings complete the armature circuit.

There are two classes of armature windings: half-coil type and full-coil type. In the alternator shown in Figure 2-3, there are four field poles and two armature coils. Thus, there is $^2/_4$ or $^1/_2$ armature coil per field pole, and the winding is called a half-coil type. The alternator of Figure 2-6 has six poles and six coils, thus there is $^6/_6$, or 1 armature coil per pole, and the winding is called a full-coil type.

Rotating Field

Alternators can supply voltages that range from a few volts to several thousand volts, and currents that range from a few amperes to several thousand amperes. For example, an alternator used to power a small radio transmitter may deliver 40 amperes at 440 volts. In this example, all of the load current is carried by the collector rings and brushes, which are insulated to withstand the maximum output voltage.

When alternators supply high voltages, arcing between the collector rings and frame becomes a problem. One way to solve this problem is to use two or more separate windings, each having its own pair of collector rings and brushes. The windings can be connected in series outside the alternator to obtain the desired high voltage. In this way, each set of collector rings and brushes handles only part of the output voltage.

To simplify collector ring and brush construction, heavy duty generators are built in a different manner. Electromagnetic induction occurs whenever a conductor cuts a magnetic field. One way to do this is to HOLD THE CONDUCTOR STATIONARY AND MOVE THE MAGNETIC FIELD PAST THE CONDUCTOR. In an alternator, this method of electromagnetic induction is accomplished by mounting the field coils on the rotating part of the alternator, and mounting the armature coils on the stationary part of the alternator.

Figure 2-7 shows how most large alternators are constructed. This construction method permits permanent, well-insulated connections to the stationary armature windings, regardless of how many there are. An advantage of this type of construction is that it permits the collector rings and brushes to carry only the dc field current and voltages, which are much lower than the load voltages and currents. Another advantage is that no matter how many sets of armature coils there are, only two collector rings and brushes are needed.

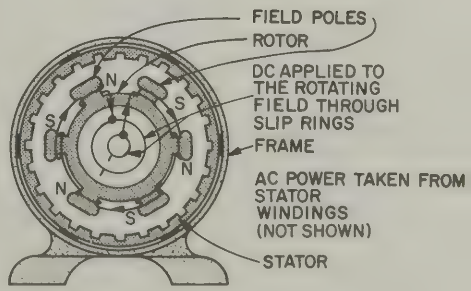
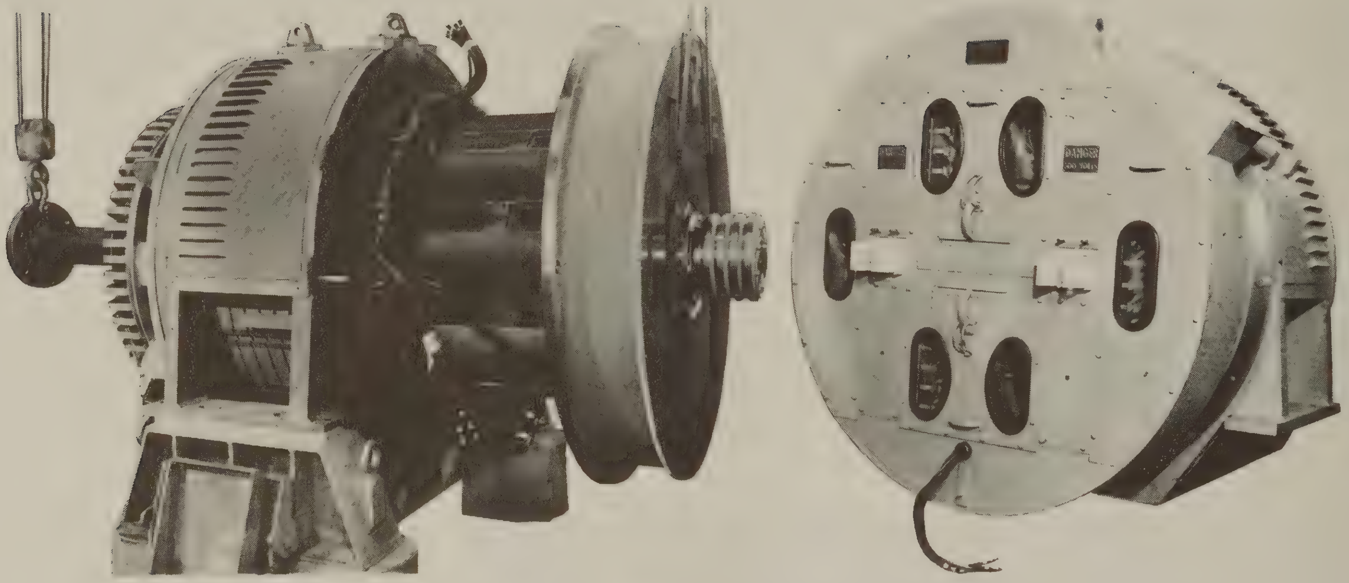

FIELD POLES
ROTOR
DC APPLIED TO THE ROTATING FIELD THROUGH SLIP RINGS
FRAME
AC POWER TAKEN FROM STATOR WINDINGS (NOT SHOWN)
STATOR
N
S
S
N
N
S

Figure 2-7

The field poles are fastened to a central rotating frame, called the **ROTOR**, which also supports the two slip rings. The external source applies the exciting current to the collector rings. The field windings are connected in series so that adjacent poles have opposite magnetic polarities.



This 3600 HP traction generator consists of two three-phase alternators. The output of the larger alternator is converted to dc by full-wave silicon rectifiers. The dc is then used to power dc traction motors. The smaller alternator provides power for fans and blowers. The photo on the left shows the rotor of the larger alternator. The photo on the right shows the end view of the 3600 HP traction generator.
Courtesy Electro-Motive Division of General Motors

The **STATOR**, or the stationary part of the alternator, is the armature. It consists of a slotted and laminated ring mounted on the inside of the frame. The winding in the slots looks like an armature winding from a dc motor or generator. The winding consists of coils which are connected into groups to produce one, two or three separate outputs.

The armature windings may be positioned around the alternator to produce output voltages that do not reach their peak at the same instant. These voltages then are of a different phase. On this basis, power may be single-phase, two-phase or three-phase. When two or more voltages of different phases are present at the same time, the result is called a **POLYPHASE** voltage.

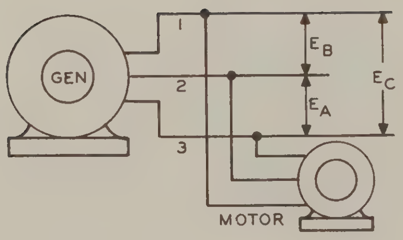


Figure 2-8

The voltage between the terminals of an alternator or motor or between the power line wires is called the **LINE VOLTAGE**. For example, in the polyphase system of Figure 2-8, the line voltages are E_A, E_B and E_C. The current in a power line wire or the current into or out of a terminal of an alternator or motor is called the **LINE CURRENT**.

Each winding of an alternator or motor, or a branch circuit forming part of a polyphase load, is known as a **PHASE**. The voltage across a phase of an alternator, ~~motor or load~~ is called the **PHASE VOLTAGE**. Likewise, the current in a phase is called the **PHASE CURRENT**.

Generating Single-Phase Voltages

Single-phase generators can be made small because they don't require many windings. This makes them a good choice for use in compact servomechanisms and other miniaturized equipment.

In a ~~single-phase~~ generator there is only one alternating voltage present. As shown by the curve of Figure 2-2, the output from the two-pole alternator of Figure 2-1 is a sinewave voltage. At any point during the cycle, only one voltage is present; therefore, it is a single-phase voltage. The device that generates the single-phase voltage is called a single-phase alternator. Despite the additional field poles and armature coils, the alternators of Figures 2-3, 2-6 and 2-7 also produce single-phase alternating current.

In general, any alternator which has the armature coils connected to provide only one electric circuit will generate a single-phase alternating current. Most of the electricity used for low-power devices is single-phase alternating current power.

Generating Two-Phase Voltages

In a two-phase alternator, the armature coils are divided into two separate groups, each group having the same number of conductors. The alternator produces equal voltages at the terminals of each group; however, the voltages differ in phase by 90°. With this arrangement, the alternator output is a two-phase voltage.

A simple two-phase alternator is shown in Figure 2-9, where a second loop has been added at right angles to loop A of the alternator shown in Figure 2-1. The ends of both loops are connected to separate collector rings, each ring makes contact with a brush. This provides two distinct circuits which are labeled A and B.

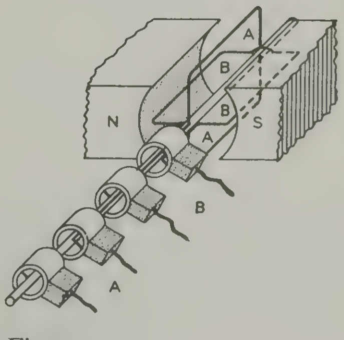


Figure 2-9

For each circuit, the voltage and current are similar to the alternator of Figure 2-1, and are represented by the curve of Figure 2-2. However,

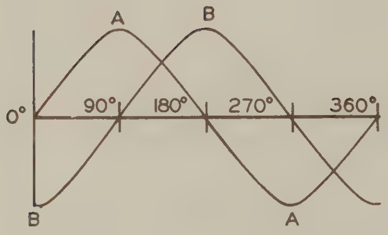


Figure 2-10

because of the positions of the loops, loop A has maximum induction when loop B has zero induction, and loop A has zero induction when loop B has maximum induction. Although the voltages have the same magnitude, shape and frequency, they differ in phase by 90°, as shown in Figure 2-10.

At the left of the figure, the voltage induced in loop A is zero while the voltage induced in loop B is maximum in a negative direction. As the armature turns 90°, the loop A voltage rises to maximum in a positive direction, and the loop B voltage decreases to zero.

Another 90° turn causes the loop A voltage to decrease to zero and the loop B voltage to increase to its maximum positive value. During the second half turn of the armature, the loop A voltage increases to its maximum negative value, and then decreases to zero. Simultaneously, the loop B voltage decreases to zero, and then increases to the maximum negative value.

At any point during the cycle, there are two separate voltages that differ in phase by 90°; therefore, the output is two-phase ac, and the device is called a two-phase alternator. Sometimes, the device is called a quarter-phase alternator because its two voltages differ in phase by one-quarter of a cycle.

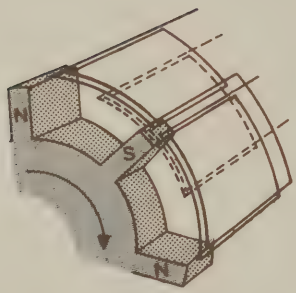


Figure 2-11

Figure 2-11 shows a partial view of a two-phase alternator using a stationary armature and a revolving field. The solid-line coil develops one phase and the dashed-line coil develops the other phase. The moving field poles are electromagnets. We have omitted the field pole windings and the rest of the armature windings for simplicity. This figure simply shows how two phases are developed using this alternator.

With the field passing through the position shown in Figure 2-11, induction is maximum in the phase represented by the solid coils. The sides of the armature loops are directly across from a field pole and are being cut by the maximum number of flux lines. The induction in the second phase, represented by the dashed coil, is minimum. The lines of flux of the moving field travel parallel to the coil sides of the second phase. Thus, when the induced emf is maximum in one phase, the induced emf is minimum in the other phase.

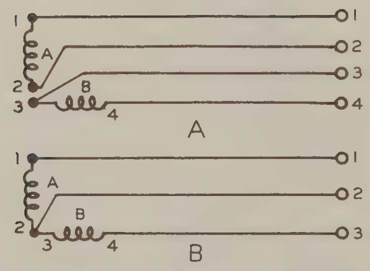


Figure 2-12

The two groups of coils may be electrically independent as shown in Figure 2-12A or they may be connected together as in Figure 2-12B. Figure 2-12A is a two-phase, four-wire system, while Figure 2-12B is a two-phase, three-wire system.

Any single-phase component, such as a simple transformer or a single-phase motor, will operate with either phase. For example, a single-phase motor will operate if it is connected to terminals 1 and 2 of Figure 2-12B. The motor will also operate if it is connected to terminals 2 and 3 of Figure 2-12B. However, a motor ~~or other component which is designed for two-phase operation must~~ be connected to both phases.

Generating Three-Phase Voltages

A three-phase alternator has three separate groups of armature coils, each with one-third the total number of conductors. The alternator produces three equal voltages that differ in phase by 120°.

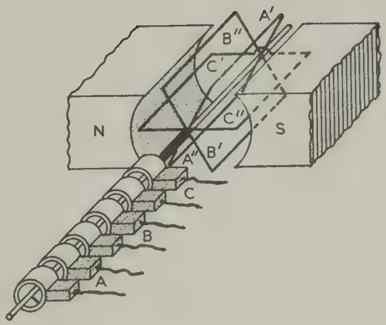


Figure 2-13

Figure 2-13 shows a simple three-phase alternator. The rotating armature has three loops spaced so that their corresponding sides are 60° apart. That is, there are 60° between sides A′ and B″, B″ and C′, and C′ and A″. Likewise, there are 60° between sides A″ and B′, B′ and C″, and C″ and A′.

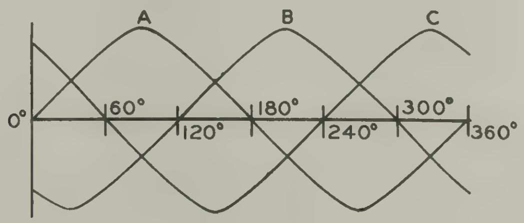


Figure 2-14

There are separate collector rings and brushes for each end of each loop; therefore, there are three separate circuits (A, B and C). When the armature turns, each loop generates a voltage similar to the one shown in Figure 2-2. However, because of the positions of the three loops, the maximum and minimum values of one voltage differ from those of the other two voltages by 120°, as shown in Figure 2-14. Note that curve A crosses the zero line at 0°, curve B crosses the zero line at 120°, and curve C crosses the zero line at 240°.

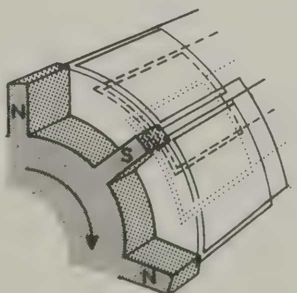


Figure 2-15

The positions of the armature windings for a three-phase alternator with a moving field are shown in Figure 2-15. The solid lines represent coils for one phase. The dashed lines represent coils for the second phase. The dotted lines represent coils for the third phase.

As in the two-phase alternator, the coils of a three-phase alternator may be independent or they may be connected together. As shown in Figure 2-13, six wires are needed to deliver the energy when independent rotating armature coils are used. In practice, the coil groups for the three phases are connected together in such a way that there are only three external wires.

Delta Connection

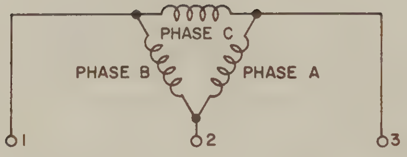


Figure 2-16

One method of interconnecting the coil groups of a three-phase alternator is shown in Figure 2-16. Because it looks like the Greek letter delta (Δ), this arrangement is called a **DELTA CONNECTION.**

It may look as though the different phases are shorted so there is no current in the external load. However, this is not so. Referring to Figure 2-14, the voltage across any one phase at a given instant is equal and opposite to the sum of the voltages in the other two phases at that same instant. For example, at the 150° instant, curves A and B cross at a point midway between zero and the maximum positive value, and curve C is at the maximum negative value. Thus, the sum of the A and B voltages is equal and opposite of the C voltage. In the internal circuit, the effective voltage is zero and no current is in the coils.

Referring to Figure 2-16, line terminals 1 and 2 connect to the ends of the phase B coils, terminals 2 and 3 connect to the ends of the phase A coils, and terminals 1 and 3 connect to the phase C coils. The voltage between any pair of terminals is equal to that induced in the armature windings of one phase. Thus, in the case of a delta-connected alternator, the phase and the line voltages are equal.

Because of the armature coil positions, the currents produced when an external load is connected to the alternator differ in phase by 120° and cannot be added arithmetically. Therefore, these currents must be added vectorially. As a result, the current in any one line wire is 1.73 times the current in one phase. The phase current is 1 ÷ 1.73, or .576 times the line current.

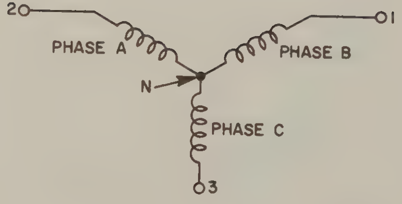


Figure 2-17

Y Connection

The second method of connecting three-phase alternators for three-wire operation is the star or **Y CONNECTION** shown in Figure 2-17. Neutral point N could be connected to an earth ground or to a fourth line wire in certain applications.

Referring to Figure 2-17, line terminals 1 and 2 connect to the end of phase coils A and B, placing these windings in series between the terminals. Phase coils A and C are connected in series between line terminals 2 and 3, and phase coils B and C are connected in series between line terminals 1 and 3.

Like the phase currents of the delta-connected armature, the voltages across the coils of a Y-connected armature differ in phase by 120°, and are added vectorially to determine the line voltage. The line voltage is 1.73 times the phase voltage. The phase voltage is 1 ÷ 1.73, or .576 times the line voltage.

Although single-phase equipment operates when connected between any two lines of a three-phase system, motors and other equipment built for three-phase operation must be connected to all three wires.

AC MOTOR OPERATION

AC motors are widely used in such applications as in clocks, appliances, tools and recording equipment. Some ac motors operate at a fixed speed which is determined by the frequency of the ac power. An electric clock keeps accurate time because it is synchronized with the alternating current that operates it. Record player or tape recorder speed is constant for the same reason. You will find many similar applications in industry. In this lesson, you will learn the principles and uses of these motors and generators built for ac operation.

Synchronous Motors

Like a dc generator, which runs as a motor when the armature as well as the field is connected to a dc source, an alternator will also run as a motor when connected to an ac source. A motor constructed on this principle runs in step with the ac source and is called a **SYNCHRONOUS MOTOR**.

The speed of a synchronous motor is controlled by the frequency of the ac power source. This does not mean, however, that the motor must run at the same speed as the alternator producing this power. The speed of a synchronous motor depends upon the number of field poles and the supply frequency.

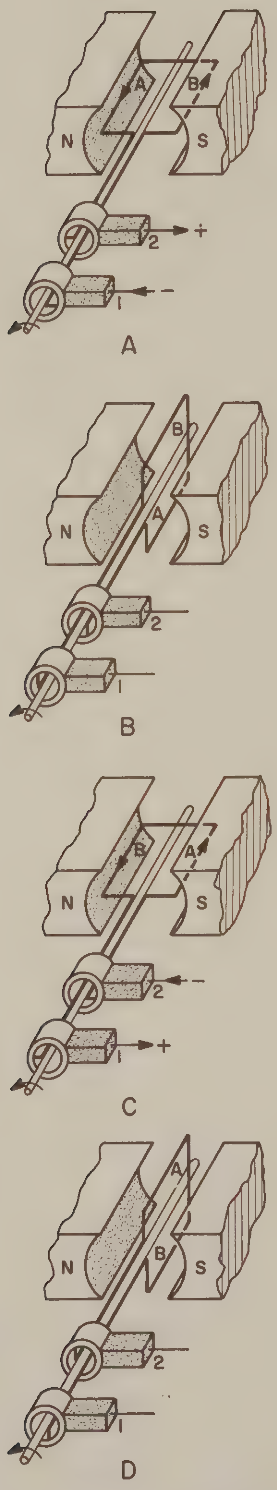


Figure 2-18

Using Equation 7, the synchronous speed of the 60 Hz motor shown in Figure 2-18 is:

$$\begin{aligned} \text{rpm} &= \frac{120f}{P} \\ &= \frac{120f}{2} \\ &= \frac{120 \times 60}{2} \\ &= \frac{7200}{2} \\ &= 3600. \end{aligned}$$

Many of the synchronous motors, especially the large ones, are not self-starting. They are brought up to the proper speed by an auxiliary device. Then, they lock in step with the supply, and run at a speed that depends on the supply frequency and the number of field poles.

To show the starting and operating conditions of a synchronous motor, the brushes of the two-pole, single-loop motor of Figure 2-18 are connected to a source of single-phase, 60 Hz ac. To begin with, the loop is in the position shown in Figure 2-18A.

When the applied voltage makes brush 1 negative and brush 2 positive, electrons flow around the circuit in the direction of the arrows. Using the three-finger, right-hand rule, the resulting torque tends to move the armature in a counterclockwise direction. However, before the torque can overcome the armature inertia, the ac polarity reverses, and brush 1 becomes positive and brush 2 negative. Now the electrons flow in the opposite direction and the torque tries to turn the armature clockwise.

Thus, the turning force acts first in one direction and then the other, changing direction very rapidly. The armature may vibrate but it will not turn. This is why many synchronous motors cannot be started by the interaction of the flux of the field and armature alone.

If the armature of a synchronous motor is rotated at a speed near its synchronous speed, it will lock in step ~~with the applied~~ voltage. The rotor is then carried around at synchronous speed by the interaction of the flux of

The following Practice Exercise questions cover the subjects which you have just studied. They are:

AC GENERATOR OPERATION

A SIMPLE ALTERNATOR

A FOUR-POLE ALTERNATOR

ALTERNATOR FREQUENCY

ALTERNATOR CONSTRUCTION

ROTATING FIELD

GENERATING SINGLE-PHASE VOLTAGES

GENERATING TWO-PHASE VOLTAGES

GENERATING THREE-PHASE VOLTAGES

29. The ends of the rotating loop windings in an alternator connect to (a) commutator segments, (b) collector rings.

30. The purpose of collector rings and brushes in an alternator is to change the connections between the rotating loop and the external circuit. True or False?

31. In the three-finger, left-hand rule, the forefinger shows the direction of (a) current, (b) flux, (c) wire movement.

32. The current in the load of Figure 2-1 periodically reverses direction. True or False?

33. The alternator of Figure 2-3 generates two complete electrical cycles for (a) each mechanical revolution, (b) two mechanical revolutions, (c) one-half of a mechanical revolution.

34. If an alternator has four poles and its armature rotates at 1800 rpm, what is the alternator output frequency?

$66\frac{2}{3}$

35. If an alternator has a 400-Hz output and its armature rotates at 4000 rpm, how many poles does the alternator have?

36. The field windings of Figure 2-6 must be energized by (a) alternating current, (b) smooth direct current, (c) pulsating dc.

37. The stationary windings in a rotating field alternator are known as the (a) rotor, (b) stator, (c) field.

38. In the two-phase alternator of Figure 2-11, the voltages in the two armature windings are maximum at the same time. True or False?

39. In a three-phase alternator the output voltages are (a) 120° apart, (b) 90° apart, (c) in phase.

40. In a delta-connected alternator, the phase and line voltages are equal. True or False?

41. In a delta-connected alternator, current in one line wire is (a) equal to the current in one phase, (b) 1.73 times the current in one phase, (c) .576 times the current in one phase.

42. In a Y-connected alternator, the phase and line voltages are equal. True or False?

field and armature. This will only happen, however, if the armature is brought up to speed by some external means.

Assume that the armature of Figure 2-18 is revolving at a synchronous speed in a counterclockwise direction. At the instant shown in Figure 2-18A, the applied voltage is maximum and of a polarity that makes brush 1 negative and brush 2 positive. As a result, electrons flow back along loop side B and forward along loop side A. Applying the three-finger, right-hand rule, the resulting torque turns the armature counterclockwise.

As the armature turns toward the position shown in Figure 2-18B, the applied voltage and the torque decrease to zero, but armature momentum carries the armature past the neutral plane. Just as the armature passes the position shown in Figure 2-18B, the applied voltage begins to rise, but this time brush 1 is positive and brush 2 is negative. Electrons flow back along loop side A and forward along loop side B. However, now the loop is turned over so that loop side A is approaching the S pole and side B is approaching the N pole. The torque has the same direction as before, and aids the counterclockwise rotation.

Both the voltage and the torque increase until the loop reaches the position shown in Figure 2-18C, after which they decrease to zero. Because of its momentum, the armature does not stop when the voltage and torque are zero, but it moves past the position of Figure 2-18D. At this point, the supply voltage reverses polarity and provides a torque that keeps the armature moving in the counterclockwise direction.

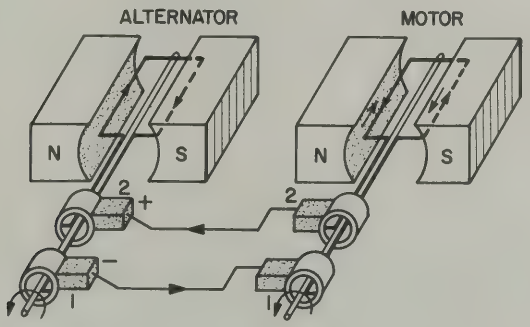


Figure 2-19

Like dc motors, ac motors generate a counter emf in their armature conductors when they are in operation. This counter emf opposes the supply voltage. To illustrate this condition, Figure 2-19 shows 2 two-pole, single-loop devices connected together. The device at the left is an alternator and is driven counterclockwise at a steady speed by an engine or a motor. The other device is a motor that is turning at a synchronous speed.

Using the three-finger, left-hand rule, the direction of induction in the alternator loop is back along the loop side near the N pole and forward along the loop side near the S pole. As a result, electrons flow around the circuit in the direction of the arrowheads.

In the motor loop, electrons flow back along the loop side near the S pole and forward along the loop side near the N pole. Using the three-finger, right-hand rule shows that the resulting torque causes the armature to turn in a counterclockwise direction. As the armature turns, its conductors are cut by the field flux and have a voltage induced in them. Using the three-finger, left-hand rule shows that the direction of this induced emf is back along the loop side near the N pole and forward along the loop side near the S pole, as shown by the small arrows near the loop sides.

Known as a reverse voltage, this counter emf opposes the applied voltage and limits the current. With identical loops turning at exactly the same speed and in the same relative positions, the applied and reverse voltages are exactly equal, and the armature current is zero. With no current in the circuit, there is no torque to keep the armature turning.

However, bearing and air friction cause the position of the motor loop to drop slightly behind that of the alternator loop. As a result, the reverse voltage lags the applied voltage by more than 180°, so that at any instant, they are not exactly equal and opposite. The differences of voltage cause current in the circuit.

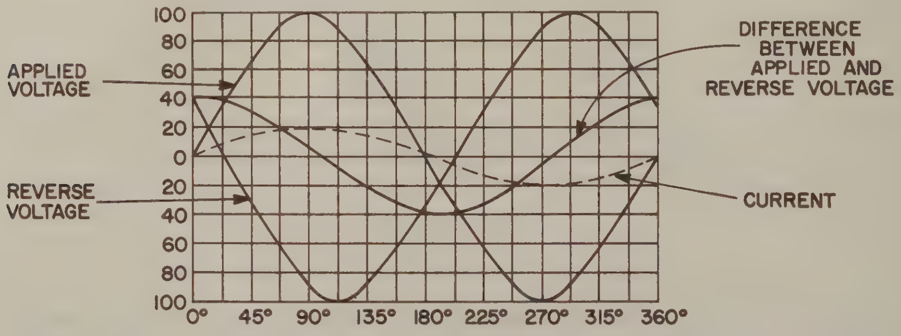


Figure 2-20

Figure 2-20 shows the conditions in the motor when its armature lags behind the alternator armature by 22.5°. The scale across the bottom shows the angle of lag, both electrical and mechanical. The vertical scale at the left shows the percentage of maximum applied voltages.

Starting at the left of the figure, the applied voltage curve crosses the zero voltage line at 0°, increases to the positive maximum at 90°, decreases to zero at 180°, increases to the negative maximum at 270°, and decreases to zero at 360°.

Because of the angular positions of the motor and alternator armatures, the reverse voltage lags the applied voltage by 22.5°. Thus, the reverse voltage curve crosses the zero voltage line at 22.5°, increases to its negative maximum at 112.5°, decreases to zero at 202.5°, increases to its positive maximum at 292.5°, and decreases to zero at 22.5° of the next cycle.

Although the curves of Figure 2-20 show the applied and reverse voltages as having the same maximum values, they are not equal and opposite. The maximum reverse voltage level is always a little less than the maximum applied voltage level. For example, at the 90° phase, the applied voltage is 100% of its maximum, but the reverse voltage is only 90% of its maximum. It is the difference between the applied and reverse voltages that causes current in the armature. Variations of this difference are labeled in Figure 2-20.

In the explanation of synchronous motor operation, the armature inductance was neglected and the current was assumed to be in phase with the applied voltage. In a regular armature however, the coil inductance may be large when compared to the resistance; therefore, the current lags the voltage. The dashed line curve of Figure 2-20 shows how the current lags the difference voltage. The current is almost in phase with the applied voltage.

When a load is placed on a synchronous motor, the motor tends to slow down. But as soon as it does, the reverse voltage lags the applied voltage, and the resulting armature current produces a torque that keeps the motor turning with a fixed lag angle at the synchronous speed. If the load is increased, the lag angle increases to permit more current and a higher torque. The torque increases as the lag angle increases until a maximum value is reached. Beyond this maximum, known as pull-out torque, the lag angle and current increase, but the torque is less and the motor stops. A synchronous motor usually runs with a displacement angle of about 20° to 25° when it is carrying full load.

Two-Phase Revolving Field

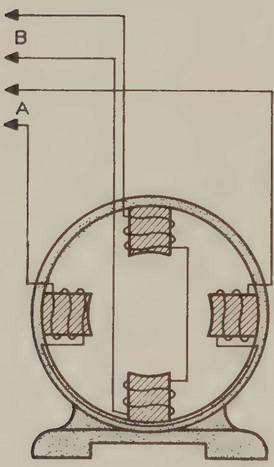


Figure 2-21

You remember that the alternator could operate with the rotor and stator conditions reversed—that is, the rotor providing the magnetic field and the stationary armature providing the ac output. The same is true of the synchronous motor. The alternating voltage can be applied to stationary windings while direct current is in the rotor coils. The action is basically the same as that just described except that the magnetic field must now rotate.

The field coils of the motor do not move physically. They are mounted in a stationary frame similar to a dc motor.

The ac variations in the field coil have the same effect as revolving the field coil. A four-pole, two-phase synchronous motor is shown in Figure 2-21. The windings on the left and right poles are in series across external terminals A, while the windings on the top and bottom poles are in series across external terminals B. In both circuits, the coil connections are arranged so that the current causes the inner pole faces to have opposite magnetic polarities.

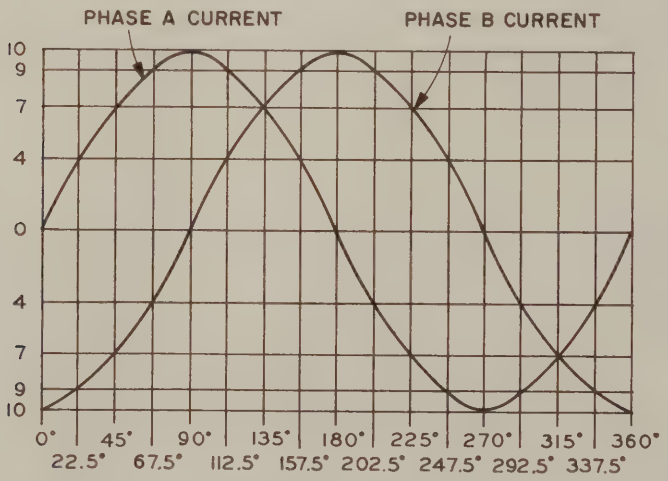


Figure 2-22

If the terminals A and B are connected to a two-phase supply, the resulting currents will be 90 electrical degrees apart as shown by the curves of Figure 2-22. Each of these currents produces a magnetic field that passes through the rotor and the stator cores. To see the action a little more clearly, assume that the vertical scale indicates the actual number of magnetic lines produced by the current.

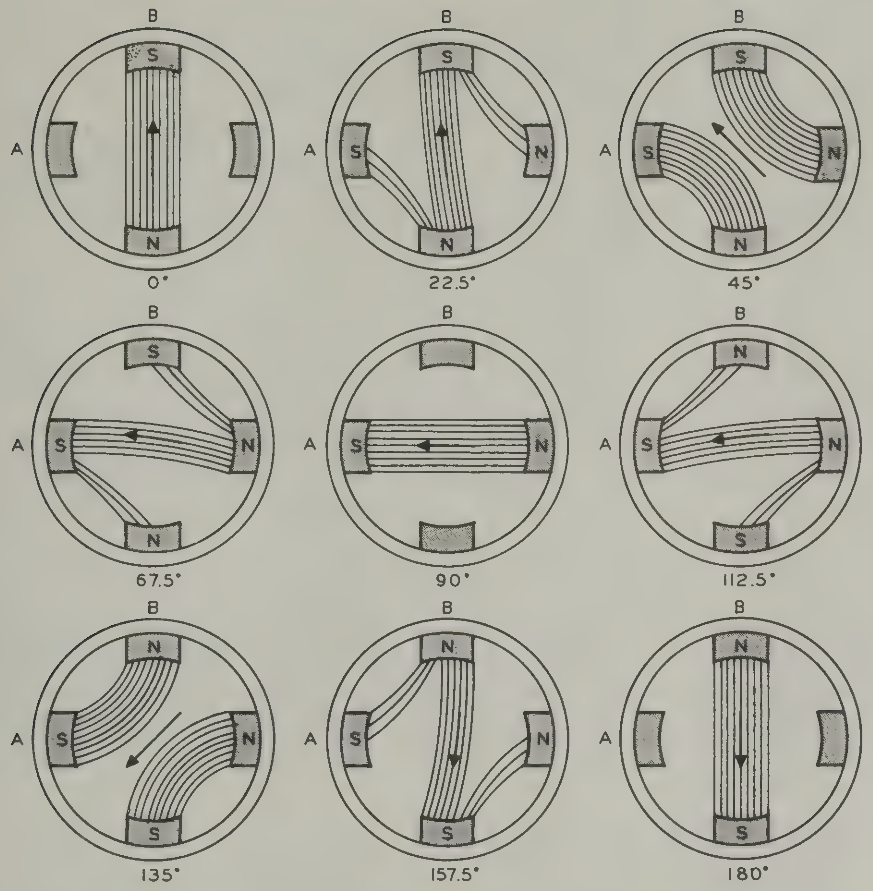


Figure 2-23

At the 0° instant of Figure 2-22, the phase A current is zero, while the phase B current is at its maximum negative value. As a result, the magnetic field consists of lines between the top and bottom poles, with the bottom pole N as shown in Figure 2-23 (0°). Because the poles of circuit A have no magnetic polarity, the flux lines go straight across the gap as shown by the central arrow.

At the 22.5° instant, the phase A current produces four lines and the phase B current produces nine lines. Like electrons, magnetic lines follow the path of least resistance. Therefore, some magnetic lines that leave the right-hand N pole bend upward and enter the S pole. Simultaneously, some of the lines that leave the bottom N pole bend to the left and enter the S pole. Figure 2-23 (22.5°) shows the interaction of the two fields. The central arrow shows that the main part of the field goes at a slight angle, and not straight across the gap between the top and the bottom poles.

At the 45° instant, both phase currents produce seven lines. At this point, all of the lines that leave the N poles bend toward the adjacent S poles, as shown in Figure 2-23 (45°). As the cycle continues, phase A current increases and phase B current decreases. At the 67.5° instant, phase A current produces nine lines and phase B current produces four lines. At the 90° instant, phase A current is at its maximum positive value and phase B current is zero, and the resultant field is at right angles to that of the 0° instant as shown in Figure 2-23 (90°).

Between 90° and 180°, phase A current decreases and phase B current increases. At the 180° instant, phase B current is at its maximum positive value and phase A current is zero. This condition is the same as that at 0°, but now the polarity is reversed so that the central arrow points downward rather than upward as shown in Figure 2-23 (180°). For the rest of the cycle, between 180° and 360°, the actions of the fields are repeated, but the polarities are reversed.

The interaction of the fields produced by the phase A and B currents distorts the total field so that its direction changes as shown by the central arrows in Figure 2-23. Although the poles are stationary, the magnetic field revolves, and completes one revolution during each cycle of the ac supply.

Three-Phase Revolving Field

Revolving fields are also produced by a three-phase supply, when there are at least three pairs of poles. One arrangement of poles and connections for a three-phase synchronous motor is shown in Figure 2-24.

Phase A is connected to the center and the bottom line wires to complete a circuit through the windings on the left and right poles. Phase B is connected to the center and top line wire to complete a circuit through the upper right and lower left pole windings. Phase C is connected to the top and bottom line wires to complete a circuit through the upper left and lower right pole windings. Tracing the circuit shows that the field windings are delta-connected.

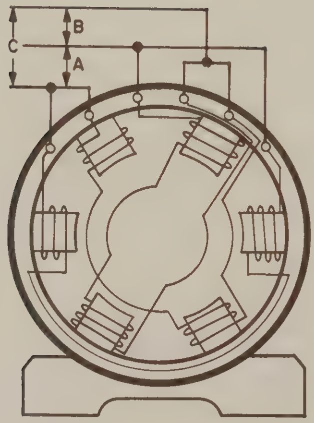


Figure 2-24

For any one phase the motor shown in Figure 2-24 is a two-pole motor. However, with a pair of poles for each phase a two-pole, three-phase motor results. Because the phase difference is 120°, the vertical coordinates of Figure 2-25 are drawn every 30°, instead of every 22.5° as in Figure 2-22. The left vertical scale of Figure 2-25 represents the phase current in amperes.

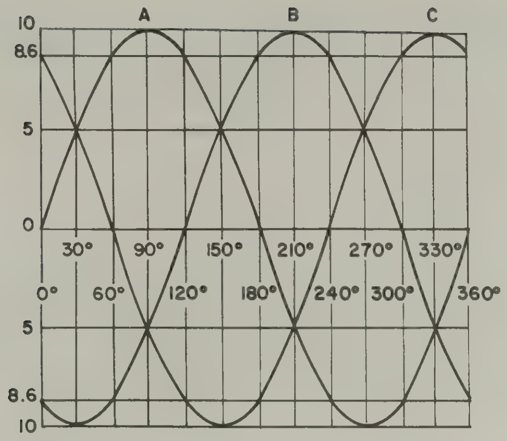


Figure 2-25

At the 0° instant, the phase A current is zero, the phase B current is a negative 8.6 amperes, and the phase C current is a positive 8.6 amperes. As a result, the magnetic field consists of lines of force between the poles of phases B and C. Because the A poles have no magnetic polarity, no flux lines go to them. Thus, the general direction of the field is straight up and down as shown in Figure 2-26 (0°).

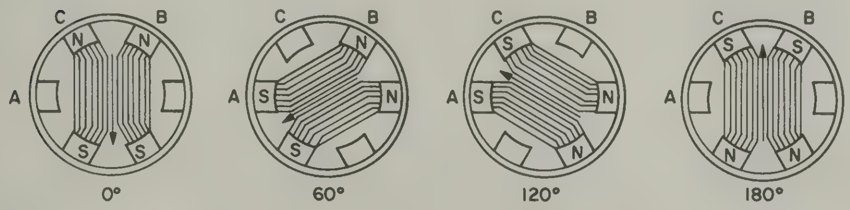


Figure 2-26

At the 60° instant, the current in phase C is zero, while in phases A and B it is 8.6 amperes. The direction of the flux lines is shown in Figure 2-26 (60°). For the 120° instant, the current in phase B is zero, and the current in phases A and C is 8.6 amperes. The magnetic field has the direction shown in Figure 2-26 (120°). Another 60° of rotation brings the flux to the position shown in Figure 2-26 (180°). This field is in the same position it occupies at 0°, but the polarity is reversed. For the rest of the cycle, the actions of the fields are repeated with the polarities reversed.

For simplicity the rotor is not shown in Figures 2-21 and 2-24. The magnetic field of a rotor supplied with dc through brushes and slip rings would react with the revolving fields of either Figure 2-21 or 2-24 to produce a torque. This torque turns the rotor in the same direction as the revolving magnetic field.

Hysteresis Motors

A **HYSTERESIS MOTOR** is a self-starting motor using a cylindrical rotor made of a magnetic alloy. This alloy is usually cobalt steel. After acceleration, a hysteresis motor operates at a synchronous speed. For this reason the motor is sometimes called a HYSTERESIS SYNCHRONOUS motor.

Hysteresis motors have many advantages. Operation of a hysteresis motor is smooth and quiet. Also, a hysteresis motor has a high-starting torque, about equal to full-load torque. Because of this constant torque, a hysteresis motor will accelerate to the synchronous speed any load which it can operate at the synchronous speed. Hysteresis motors operate at low efficiency, but the good speed characteristics usually outweigh this disadvantage.

There are basically two types of hysteresis motors. One type is designed to operate from a single-phase source, the other type is designed to operate from a polyphase source. Hysteresis motors which operate from a single-phase source are commonly found in tape recorders, record changers and electric clocks. You will notice that all these uses require a constant-speed motor.

In the single-phase hysteresis motor, the same starting problem exists as in other single-phase motors. A revolving field must be produced or the motor will not start. A shading coil or a deformed field pole is used to provide a shift in the magnetic field. Once the rotor turns, the motor operates on the principle of hysteresis, as will be explained later in this lesson, and accelerates with a high torque to the synchronous speed.

Hysteresis motors which operate from a polyphase source are used primarily in industry, where larger amounts of torque are required. The following is a discussion on three-phase hysteresis motors. However, keep in mind that the same hysteresis principles which apply to three-phase motors also apply to single-phase motors.

Hysteresis is a flux density lag behind the magnetizing force. As a result of hysteresis, the changes in magnetism, induced in a material, lag the changes in the magnetizing force. If a solid cylinder of steel is used as a rotor between a pair of magnetic poles, as shown in Figure 2-27A, the rotor becomes magnetized. The molecules in the steel arrange themselves along the magnetic lines of force so that the axis of the magnetized rotor lines up with the axis of the field poles. The line A-B is the magnetic axis common to both the magnetizing field and the induced rotor magnetism.

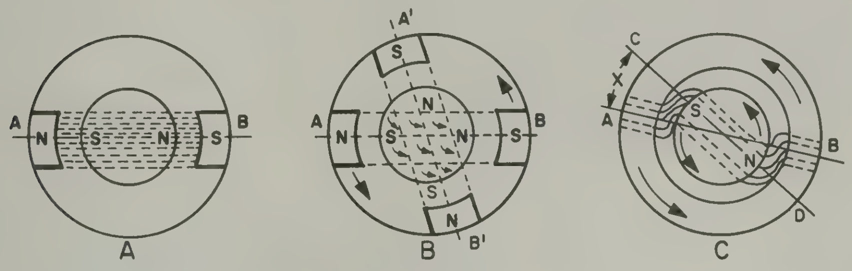


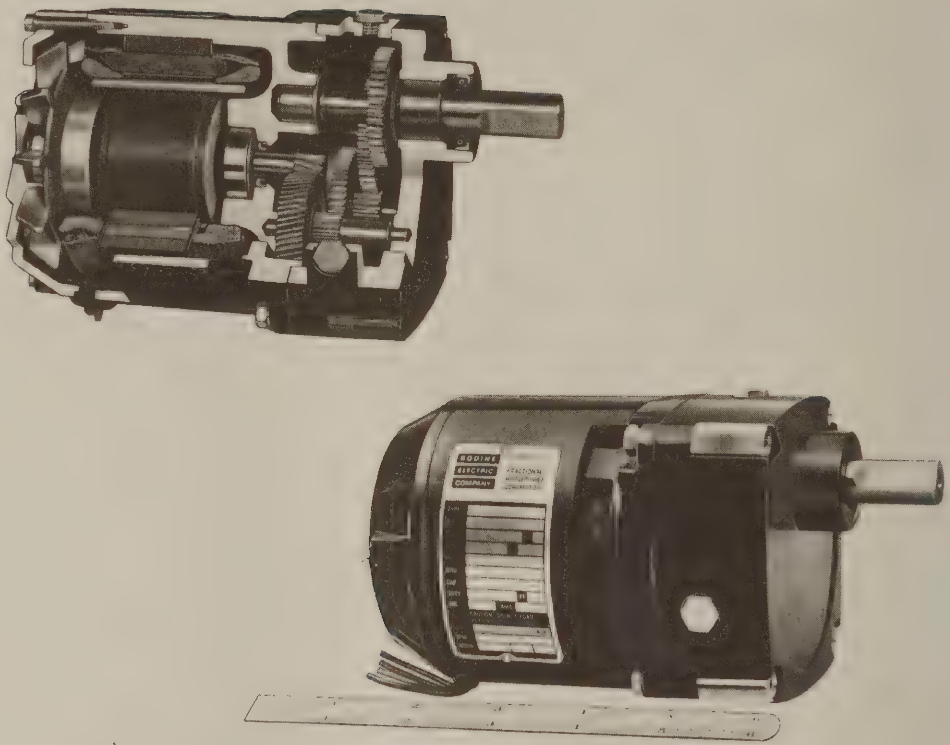
Figure 2-27

If the field poles are rotated around the rotor, the molecules in the rotor change their position, as shown in Figure 2-27B. This change in position causes them to turn and line up with the new magnetic axis A′-B′. The molecules of steel resist this change in position; therefore, their movement is always a little behind the change in position of the field poles. The magnetic axis within the rotor therefore lags a few degrees behind the magnetic axis of the revolving field. This condition is shown in Figure 2-27C, where axis A-B is the magnetic axis of the field (rotating counterclockwise) which is being followed by axis C-D caused by the magnetism induced in the rotor. The angle X is called the lag angle.

The polarity of the magnetism induced in the rotor is opposite to that of the field. The opposite poles attract and the rotor turns as it tends to line up the C-D axis and the A-B axis. As long as the field continues to revolve, the rotor will turn in an attempt to line up the magnetic axis.

The rotor attempts to accelerate to the synchronous speed of the revolving field. As long as the rotor is running slower than synchronous speed, it is subject to changing magnetic field and hysteresis will occur. The rotor magnetic axis will lag the field magnetic axis by a value equal to the hysteresis lag angle. This angle remains constant because it depends on the magnetic field, which also remains constant.

The torque developed by the rotor while building up speed is caused by hysteresis. The torque will remain constant because the lag angle does not change. When the rotor reaches synchronous speed, it synchronizes with its magnetic axis and the magnetic axis becomes stationary with respect to the rotor. The magnetic conditions in the rotor become stable and hysteresis is



This induction parallel shaft gear motor is available in ac or dc versions, and is designed for use where precise power and dependable repeatability of operation is required. The cutaway view shows the gear train and parallel shafts.
Courtesy Bodine Electric Company

greatly reduced. Because of this, the molecules in the rotor are no longer subjected to changes of polarity caused by the magnetic field revolving around the rotor. The rotor now acts as a permanent magnet and is carried around at a synchronous speed by the interaction of the flux of the field and rotor. The lag angle adjusts to varying loads and becomes zero at no load. At this time the torque is also zero.

Because the torque becomes zero when the lag angle is zero, the rotor cannot accelerate past the synchronous speed. The rotor always stays synchronized with the rotating field until a load is applied, at which time the lag angle increases. That is, when a load which the motor can operate is applied, the rotor will continue to turn at the synchronous speed. The rotor just lags behind the revolving field a little more. When the lag angle increases, the motor develops more torque and decreases the lag angle. This action happens instantaneously and the hysteresis motor runs at a very constant speed.

Induction Motors

INDUCTION MOTORS are both rugged and dependable. They require only an alternating current for their operation. They are used to drive servomechanisms, appliances and machinery of all sizes. Induction motors operate because of the induced currents in their rotors. They are built for both single-phase and polyphase operation and can be used over a wide range of frequencies.

The basic principle of induction motor operation is shown in Figure 2-28. The rotor consists of a copper cylinder mounted on a shaft and supported by bearings so that it can turn. The magnetic field is arranged so that it revolves around the armature.

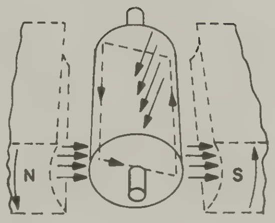


Figure 2-28

When the field poles turn in the direction of the curved arrows, the flux cuts the cylinder and induces an emf in it. Actually the field poles of Figure 2-28 do not physically rotate. We have used the revolving magnets to represent the revolving magnetic field set up by a stator with polyphase windings. This action was shown in Figures 2-23 and 2-26. As previously discussed, induction is maximum in that portion of the cylinder directly adjacent to the poles, and minimum midway between the poles. In the plane of maximum induction, the armature looks like a closed or short-circuited loop, as shown by the dashed line in Figure 2-28. Why this loop is not directly across from the magnetic poles is discussed later. Induction causes current in the direction of the arrowheads.

The outer surface of the cylinder is a continuous conductor. Not all the electrons follow the path indicated by the dashed line. Some of them flow from one end of the cylinder to the other along the surface outside the magnetic field, where induction is zero.

The greatest amount of electron flow is along the dashed line path in the direction of the arrowheads. This current sets up a magnetic field at right angles to the field flux. The N pole of this field is at the bottom of the armature, and the S pole is at the top. Because unlike poles attract, the interaction of the magnetic fields produces a torque that turns the cylinder in the same direction as the revolving field.

Unlike a synchronous motor, the armature of an induction motor cannot run at the same speed as the revolving field. It depends on the flux cutting the armature to produce the armature current and flux.

Synchronous Speed and Slip

The rate at which the field turns is known as the synchronous speed of the motor. This speed depends on the frequency of the supply and the number of poles per phase. The synchronous speed of a two-pole, two-phase motor operating from a 60-Hz supply is found by using Equation 7:

$$\begin{aligned} \text{rpm} &= \frac{120f}{p} \\ &= \frac{120 \times 60}{2} \\ &= \frac{7200}{2} \\ &= 3600. \end{aligned}$$

The induction motor rotor always turns at a speed slower than that of the field, so that enough torque is produced to meet the demand of the load. The difference between the rotor speed and the field speed is called the **SLIP.** Expressed as a percentage of the synchronous speed, slip is found by the following equation:

$$S = \frac{ss - sr}{ss} \times 100 \tag{8}$$

where:

S is the slip in percent of synchronous speed.
ss is the synchronous speed, and
sr is the rotor speed.

As an example, a four-pole motor operating from a 60-Hz supply has a synchronous speed of 1800 rpm, but the rotor speed is 1725 rpm. Under these conditions,

$$\begin{aligned} S &= \frac{1800 - 1725}{1800} \times 100 \\ &= \frac{75}{1800} \times 100 \\ &= 4.1\%. \end{aligned}$$

As the load increases, the rotor speed decreases and the slip increases. The greater the slip the more induction. This action increases the torque to meet the demand of the load. When enough torque is developed, the motor operates at a constant speed and slip until the load changes.

Induction Motor Rotors

A copper cylinder is shown in Figure 2-28, but as previously discussed, the current caused by the induced voltage has no definite path. The flux produced by the current is not all in the same direction; therefore, the torque produced on the armature is not very strong. More torque results if slots are cut in the cylinder surface. Not only does this keep the current in definite paths to increase the torque, but it also reduces the armature weight.

In any motor, the torque depends on the armature current and the strength of the magnetic field. The magnetic field, in turn, depends on the reluctance, or opposition to lines of force, of the gap between the magnetic poles. If the cylinder of Figure 2-28 is filled with iron, the reluctance will be reduced so that the magnets can produce a stronger field. As a result, induction is increased, there is a higher armature current, and a greater torque is developed.

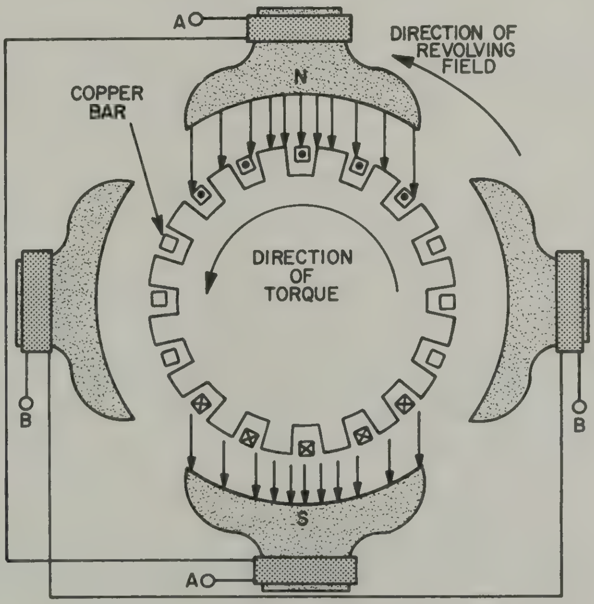


Figure 2-29

The rotor of an induction motor consists of a laminated iron core with slots around its outer rim. These slots contain a winding made of copper bars connected together at the ends by copper rings. Sometimes the bars and rings are all cast in one piece. A rotor of this type, shown in Figure 2-29, is called a **SQUIRREL-CAGE ROTOR.** The rotor has no electric connections to the field or the supply line.

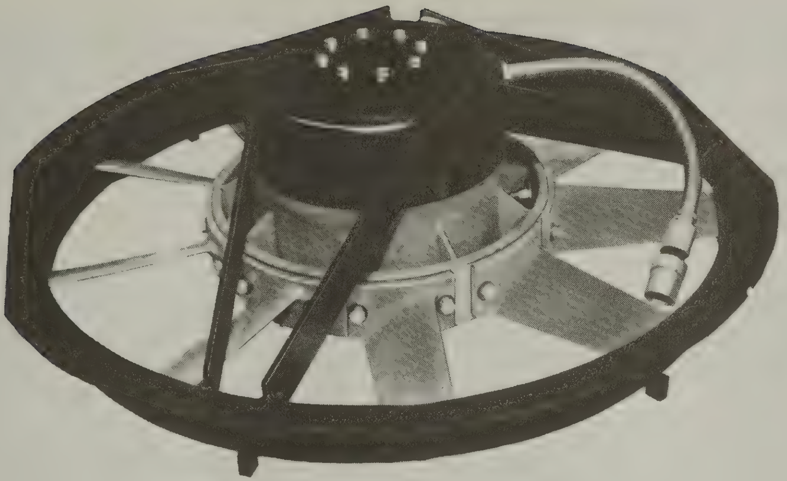
If the rotor of a two-phase or three-phase induction motor is acted upon by the revolving magnetic field, the flux will cut the rotor conductors and induce an emf in them. As shown by the greater concentration of arrows in Figure 2-29, the flux density is greatest directly under the center of the poles; therefore, the induced emf is greatest at this point. This emf causes a current in the rotor conductors because they are short-circuited by the end rings.

With the field turning in a counterclockwise direction as shown by the outer curved arrow of Figure 2-29, the three-finger, left-hand rule shows that the current direction is out of the conductors under the N pole and into those under the S pole. As a result of this current, a force is placed on the armature conductors. The three-finger, right-hand rule shows that the torque is in the same direction as the field rotation.

If the rotor is free to turn, it will turn in the same direction as the field and tend to reach the same speed. However, as the rotor speed increases, the rotor conductors are cut by the revolving field at a slower rate, which results in a decrease of current and torque. Upon reaching the same speed as the field, the flux stops cutting rotor conductors, which results in no induced emf and no turning torque.

Therefore, an induction motor rotor always runs slightly slower than the revolving field, even with no load. This is because a small torque is needed to overcome the bearing friction and other losses. As the mechanical load on the motor is increased, more rotor current is needed to produce the necessary torque. Because of the laws of electromagnetic induction, the induced emf and current are proportional to the rate of cutting, and the rotor speed is reduced to increase them. In ordinary squirrel-cage induction motors, a change of rotor speed of about 5% is enough to produce the torque necessary to carry the full load.

Another type of induction motor rotor has a winding, commutator and brushes like those of a dc motor or generator. However, the brushes are not connected to a voltage source. Instead, the brushes are electrically connected together. The brushes short-circuit the rotor windings as they pass beneath a field pole. When the field windings of this type of motor are connected to an ac supply, the induced emf causes a high current in the coils to which the brushes are connected, and a low current in the rest of the coils. As a result, the motor develops a very high-starting torque. When the motor reaches its normal running speed, a centrifugal switch short-circuits all of the commutator bars and the motor operates as a squirrel-cage induction motor. A



This cooling fan uses a three-phase inverted squirrel-cage induction motor. The rotor is located outside of the stator and it rotates with the fan.
Courtesy Electro-Motive Division of General Motors

motor of this type is called a repulsion-start, induction-run motor, or simply a repulsion-induction motor.

Some fan motors are constructed with the rotor as part of the fan blade casting or assembly that revolves around the stator. These fans usually have one bearing and are mounted so that the axis of rotation is vertical (the fan moves the air up or down).

Single-Phase Induction Motor

In many locations polyphase ac power is not available. For this reason, many smaller induction motors are built to operate on single-phase ac. If external terminals A of the motor shown in Figure 2-29 are connected to a source of single-phase ac, the resulting magnetic field does not revolve. The polarity reverses during each succeeding alternation, but no emf is induced in the armature conductors and no turning force is produced. However, once the rotor is started, it will continue to operate and will gain speed until it is operating at its normal speed.

To show how an induction motor can run with a reversing field rather than a revolving one, assume that the top and bottom field poles of Figure 2-29 are connected to a source of single-phase ac, and that the rotor is spinning in a counterclockwise direction, as shown by the inner curved arrow. Because only one set of coils is energized, the field is stationary.

Because of the applied voltage, the field current has the waveform of curve A in Figure 2-22. At the 0° phase, the current is zero, there is no induction, and no torque is produced. However, the momentum of the heavy rotor keeps it spinning at an almost constant speed during this interval. A moment later, the current reaches maximum and a strong magnetic field is produced. Although the field flux is stationary, the conductors are moving, and an emf is induced in them as they pass the S and N poles.

Because of this induced emf, electrons will flow in the same direction and magnetize the rotor core so that it has an S pole at the left and an N pole at the right.

The rotor winding is highly inductive; therefore, the rotor current lags the rotor emf by nearly 90°. Thus, the maximum flux value set up by the rotor current differs (by 90°) from the maximum flux value set up by the stator windings. Because the two fields are 90° apart, they act like the two fields set up by the stator windings of the two-phase motor shown in Figure 2-21. They combine to produce a rotating field that will drive the rotor in the same manner as in the two-phase motor.

A single-phase motor of the type just described will run in either direction. depending on the way it is started. Single-phase motors are usually made self-starting by producing two out-of-phase outputs from the same input. This is done to produce a revolving field which starts the motor in the desired direction.

Capacitor Motor

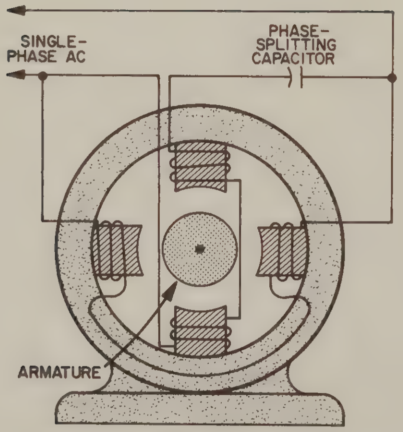


Figure 2-30

One way of providing two-phase field excitation from a single-phase supply is to connect one set of field windings directly across the power line, and the other set of field windings across the line in series with a capacitor. This results in the **CAPACITOR MOTOR** shown in Figure 2-30. Because capacitance causes the current to lead the applied voltage, there is a phase difference between the currents in the vertical and the horizontal coils. In effect, the currents approach the conditions shown by the curves of Figure 2-22, and the magnetic field they produce turns at a synchronous speed.

The revolving field acts on the rotor to keep it turning. A capacitor motor has a high-starting torque and a high pull-out torque. For this reason, it is ideal for use in high-speed blowers, pumps, power tools and appliances.

In the capacitor motor, the phase-splitting capacitor carries the current in one set of windings all the time the motor is operating. Any leakage between the plates will heat the capacitor excessively; therefore, a high-quality capacitor is used.

Capacitor-Start Motor

It is possible to use the advantages of the capacitor motor's high-starting torque only during the starting interval. A starter switch is connected in series with the phase-splitting capacitor and the motor winding. The switch is mounted on one end of the housing and one end of the rotor. Operated by centrifugal force, the starter switch opens the capacitor circuit when the rotor approaches its normal running speed. Thus, the motor starts as a two-phase type and runs as a single-phase type.

When a switch is used to disconnect the capacitor, the motor is known as a **CAPACITOR-START MOTOR.** Coils in series with the capacitor are known as the starter windings. Because the capacitor is only used for starting, it does not have to be a high-quality capacitor. The capacitor-start motor is most widely used in washing machines, dryers, furnaces, pumps and refrigerators.

Split-Phase Motor

Inductance can also be used to produce the phase shift between the currents in the two sets of windings. In this instance, the coils of one set of windings are wound with many turns of small wire and connected in series with a starter switch across the line. The higher inductance causes the current in one set of windings to lag the current of the other set of windings. As in the capacitor motor, the phase shift between the two currents produces a revolving field that starts the motor. When the rotor approaches its normal speed, a centrifugal switch opens and disconnects the starter windings. This type of motor is called a **SPLIT-PHASE MOTOR.**

The split-phase motor has the same general characteristics as a capacitor-start motor and it can be used in the same applications.

Shaded-Pole Motors

Still another method is sometimes used to obtain a phase shift for starting small motors. In the capacitor and split-phase motors, shifting the phase of the current in a second set of windings results in a shifting of the magnetic

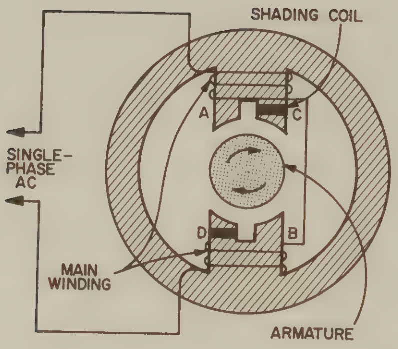


Figure 2-31

field. It is possible to shift the magnetic field at the pole by the method shown in Figure 2-31.

The current in the main winding produces poles A-C and B-D as in the previous induction motors. However, pole tips C and D each have an extra winding. These extra windings, called **SHADING COILS,** are actually made up of one or more short-circuited turns of copper around each pole. A motor using this type of construction is called a **SHADED-POLE MOTOR.** The current induced in the shading coils causes the flux at poles C and D to lag behind the flux at A and B. This lag produces a revolving field; therefore, the motor becomes self-starting. The starting torque is small; therefore, these motors are limited to light duty uses. They are simple to build and low in cost.

Reversing Induction Motors

The direction in which an induction motor starts depends on the phase relation of the magnetic fields. The operating direction is reversed by reversing the connections of any one set of windings. For example, the connections of the circuit A coils in Figure 2-29 are arranged so that when the bottom A terminal is positive, the bottom pole is S and the top pole is N. As a result, the magnetic field turns in a counterclockwise direction.

If the polarities of the A terminals are left unchanged, but the coil connections to those terminals are reversed, the magnetic polarity will reverse also. Thus, the bottom pole will be N, the top pole will be S, and the resultant field will rotate clockwise. Because it is pulled along by the revolving field, the rotor also spins in a clockwise direction.

Universal Motors

A motor that is commonly used in small household appliances and small tools, such as mixers, sewing machines, electric drills and electric shavers, is the universal motor. A universal motor has brushes and a commutator, and will operate on either ac or dc. It is basically a series dc motor. The direction of rotation of a series dc motor is the same regardless of the polarity of applied voltage, provided there is no change in the relative connections of the armature and field. Therefore, if the motor is connected to a single-phase ac source, the resulting torque is always in the same direction; and the motor operates using ac as well as dc.

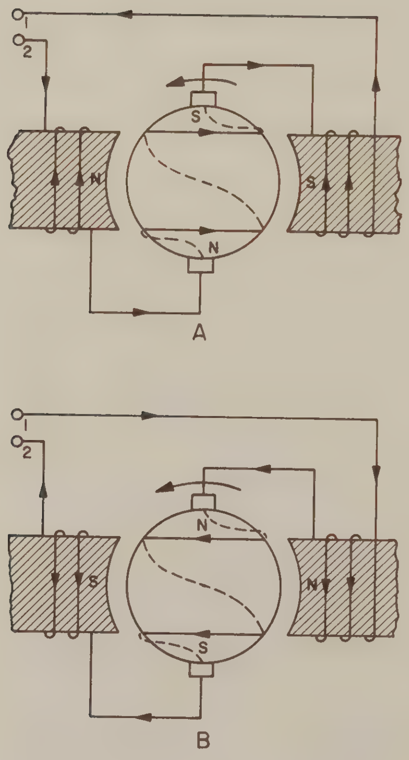


Figure 2-32

To illustrate the details of ac operation, Figure 2-32 shows the electric and magnetic circuits of a two-pole series motor. During the ac supply alternation when terminal 1 is positive and terminal 2 is negative, electrons flow in the direction of the arrowheads in Figure 2-32A. With current in the direction shown, the left pole is N, the right pole is S, the bottom of the armature is N, and the top is S. Because of the attraction of unlike poles, the armature rotates. The three-finger, right-hand rule indicates counterclockwise armature rotation.

In the next alternation, the supply polarity reverses so that the electrons flow in the opposite direction as shown in Figure 2-32B. Now, the left pole is S, the right pole is N, the armature bottom is S, and the top is N. Although the current direction and magnetic polarities are reversed, the interaction of the two fields still produces counterclockwise rotation.

Because they will operate from dc as well as 60 Hz ac, universal motors are found in many appliances. When operating under a heavy load, universal motors spark excessively, and may produce serious radio interference.

POWER FACTOR

The power factor of an alternating current circuit is the ratio of true power to apparent power. For sinewaves, the power factor can also be expressed as the cosine of the phase angle (θ) between the current and voltage, or pf = $\cos \theta$.

With a resistive load, E and I are in phase, θ is zero, and the power factor is 1, or unity. As the circuit becomes inductive or capacitive, current begins to lag or lead the voltage. The power factor decreases to zero when θ reaches 90°. Therefore, the power factor may have any value between zero and 1.

Because the numerical value of the power factor is the same whether the current leads or lags, you must always state if the current is leading or lagging. Generally, the term "lagging power factor" means that current lags voltage.

For induction motors, the power factor depends on the winding type and the gap between the stator and rotor. At full load, the power factor is about .8 to .93, depending on the motor size and the number of poles. Squirrel-cage induction motors have starting power factors in the range of .3 to .4, while wound rotor types have starting power factors on the order of .6 to .65. The power factor of an induction motor is very low at light loads; therefore, it is desirable to select the motor so that it is well loaded under normal running conditions.

SINGLE-PHASE AND POLYPHASE CIRCUIT POWER

For single-phase ac circuits, the true power in watts is given by the equation:

$$P_T = I \times E \times pF \tag{9}$$

where:

P_T is the true power in watts,
I is the line current in amperes,
E is the line voltage in volts and
pF is the circuit power factor.

To illustrate the power calculation, assume that the voltage is 440 volts, the current is 10 amperes, and the power factor is .9. The true power is:

$$\begin{aligned} P_T &= I \times E \times pF \\ &= 440 \times 10 \times .9 \\ &= 3960 \text{ watts.} \end{aligned}$$

In a two-phase ac circuit, each phase is treated like a single-phase circuit, and the total power is found by adding the individual powers.

Electric instruments usually show the line voltage and current in a three-phase circuit. However, the phase voltage of a three-phase, Y-connected armature is equal to .576 times the line voltage. The true power developed in one phase is:

$$P_T = .576 \times I \times E \times pF \tag{10}$$

where:

P_T is the true power in watts,
I is the line current in amperes,
E is the line voltage in volts and
pF is the power factor.

If all of the currents and voltages are equal, the system is balanced, and the true power for all three phases is:

$$\begin{aligned} P_T &= 3 \times .576 \times I \times E \times pF \\ &= 1.73 \times I \times E \times pF. \end{aligned}$$

For example, assume that the voltage is 440 volts, the current is 10 amperes, and the power factor is .9. The true power is:

$$
\begin{aligned}
P_T &= 1.73 \times I \times E \times pF \\
&= 1.73 \times 10 \times 440 \times .9 \\
&= 6850 \text{ watts.}
\end{aligned}
$$

If the load is unbalanced, the total power is the sum of the individual powers.

Because the phase current of a delta-connected armature is .576 times the line current, the true power for a delta connection figures out the same as for the Y connection, and the same equation can be used for both.

EFFICIENCY

A certain amount of the energy delivered to an alternator or motor is lost within the device in the form of heat. These losses may be summarized as follows:

Copper Losses—Power losses caused by current in the stator and rotor cores.

Iron Losses—Power losses caused by eddy currents and hysteresis in the stator and rotor cores.

Friction Losses—Power losses caused by the friction of the bearings and friction of the air against the spinning rotor.

The efficiency of an alternator or motor, in percent, is given by the equation:

$$\% \text{ Eff.} = \frac{\text{output}}{\text{input}} \times 100 \tag{11}$$

where the output and the input are in the same terms.

The efficiency equation may also be written as:

$$\% \text{ Eff.} = \frac{\text{input} - \text{losses}}{\text{input}} \times 100 \tag{12}$$

$$\% \text{ Eff.} = \frac{\text{output}}{\text{output} + \text{losses}} \times 100. \tag{13}$$

As an example, assume that the input to a motor is 5000 watts and the total losses equal 500 watts. What is the efficiency?

$$\% \text{ Eff.} = \frac{5000 - 500}{5000} \times 100$$

$$= \frac{4500}{5000} \times 100$$

$$= 90\%.$$

AC generators and motors seldom operate at unity power factor. When calculating efficiency, the power factor must be considered. In addition, the mechanical power input or output usually is given in horsepower and must be changed to electric power. To show this type of calculation, assume that a 440-volt induction motor draws 25 amperes at .8 lagging power factor when developing its rated output of 10 horsepower. What is the efficiency?

First, calculate the electric power output (1 HP = 746W):

$$P_O = 10 \times 746 \text{ watts}$$

$$= 7460 \text{ watts.}$$

Second, calculate the electric power input:

$$P_{IN} = 440 \times 25 \times .8$$

$$= 8800 \text{ watts.}$$

Third, calculate the efficiency:

$$\% \text{ Eff.} = \frac{7460}{8800} \times 100$$

$$= 84.7\%.$$

The efficiency of induction motors at full load ranges from approximately 85% for small motors to 92% for large motors. Hysteresis and shaded-pole ~~motors operate at very low~~ efficiencies, in some ~~cases less~~ than 1%.

MAINTENANCE OF AC MOTORS

An ac motor does not differ greatly from a dc type. Mechanically, the ac rotor corresponds to the dc armature, so the bearing maintenance is the same. Some ac motors have commutators which need the same care as those in dc motors. Other ac motors have slip rings which must be cleaned the same as commutators. The brushes which contact these slip rings must be able to move freely in their holders. Starting switches used in split-phase and capacitor-type, single-phase ac motors must be kept clean and in perfect working order. If these switches fail to open, the motor will start, but will overheat and become damaged.

The following Practice Exercise questions cover the subjects which you have just studied. They are:

AC MOTOR OPERATION

SYNCHRONOUS MOTORS

INDUCTION MOTORS

UNIVERSAL MOTORS

POWER FACTOR

SINGLE-PHASE AND POLYPHASE CIRCUIT POWER

EFFICIENCY

MAINTENANCE OF AC MOTORS

43. A large synchronous motor cannot start by itself because the ac supply reverses polarity before the motor's magnetic fields can overcome armature inertia and start turning. True or False?

44. The voltage which causes a motor armature to rotate is the difference between supply voltage and reverse voltage. True or False?

45. At values of torque below pull-out torque, when a larger load is placed on a synchronous motor, (a) torque increases, (b) torque decreases.

46. In a synchronous motor, the field poles (a) actually move, (b) are stationary but because of a polyphase connection produce a magnetic field that rotates.

47. The rotor of a hysteresis motor (a) has an even number of windings, (b) is a squirrel-cage rotor, (c) is a steel cylinder.

48. A 400-Hz motor has 8 poles. At what speed does its field turn?

49. An induction motor depends upon magnetic coils in the armature to produce flux. True or False?

50. Why is the induced current in the rotor of Figure 2-28 shown to be lagging the rotating field?

51. In a capacitor-start, split-phase motor, after a certain speed is reached, a centrifugal switch opens one set of windings and the motor runs as a single-phase motor. True or False?

52. The rotation of an induction motor cannot be reversed. True or False? Why?

53. A universal motor has (a) collector rings, (b) commutator segments, (c) neither.

54. Assume that we have a three-phase induction motor with a power factor of .8. The line current is 15 amperes and the line voltage is 220 volts. What is the true power used by the motor?

55. If a single-phase 4.5 horsepower induction motor draws a line current of 20 amperes at 220 volts and has a power factor of .9, what is the efficiency of the motor?

SUMMARY

Alternators are rotating devices used to generate alternating current. As in the case of dc generators, ac alternators with added poles are much more efficient than two-pole alternators. Alternators can be classed as either single-phase, two-phase or three-phase, depending on the number of groups of armature coils.

Motors convert electrical energy into mechanical energy. In certain applications, more than one type of motor can be used to do the same thing. However, one type may be better than the other for a given application.

Synchronous motors are constant-speed motors. They may not be self-starting, and then must be brought up to synchronous speed by some external source. In applications where constant speed is needed regardless of load, synchronous motors are used.

Induction motors provide constant speed over a wide variation of loads, and are both rugged and dependable. Because they are self-starting and run at constant speed, induction motors are used to drive many types of machinery.

Common types of single-phase induction motors are capacitor, capacitor-start and split-phase. Capacitor motors operate with a capacitor in series with a separate field winding. Capacitor-start motors use a capacitor in series with the starter winding until operating speed is reached. Inductor-start, split-phase motors use the inductance of the starter winding to produce a rotating field for starting. These motors all have high-starting and pull-out torque.

A distinct type of synchronous motor is the one called a hysteresis motor. This motor starts as a hysteresis motor and runs at a synchronous speed. In this way, both high-starting torque and constant speed are obtained. Hysteresis motors are used in tape recorders and other types of equipment that require constant synchronous speed.

IMPORTANT DEFINITIONS

ALTERNATOR—A rotating machine designed to generate an alternating current.

ARMATURE—The part of a generator or motor in which an emf is produced due to induction. Usually the rotating part of a dc motor or generator.

ARMATURE REACTION—The interaction of the flux in the field and armature.

BRUSH RIPPLE—Ripple in a generator output voltage caused by uneven contact between the brush and the commutator.

CAPACITOR MOTOR—A single-phase induction motor with a two-phase winding, one set of coils of which is connected to the line through a capacitor.

CAPACITOR-START MOTOR—A single-phase induction motor that employs a capacitor in series with the starting windings only until operating speed is almost reached. At this speed, the capacitor and starting winding circuit is opened by a centrifugal switch.

COMMUTATING PLANE—The plane at right angles to the magnetic field in which no voltage is induced in a conductor moving across the plane. Also called the NEUTRAL PLANE.

COMMUTATING POLES—Small poles placed between the main field poles to reduce the rotation of the neutral plane with load variations. Also called INTERPOLES.

COMMUTATOR—A ring of segments which provides switching of armature connections such that the output current is always in the same direction.

COMMUTATOR RIPPLE—Ripple in a generator output voltage caused by uneven voltage distribution between adjacent commutator segments.

COMPOUND GENERATOR—A generator in which the field windings are partly in series and partly in shunt with the armature.

COUNTER EMF (cemf)—The emf induced in the inductors of a motor armature when it is spinning in a magnetic field.

CUMULATIVELY-COMPOUNDED GENERATOR—A compound generator in which the flux of the shunt and series fields aid each other.

CUMULATIVELY-COMPOUNDED MOTOR—A compound motor in which the flux of the shunt and series fields aid each other.

IMPORTANT DEFINITIONS (Continued)

DELTA CONNECTION—The connection of a three-phase system so that the phases form a triangle like the Greek letter delta (Δ).

DIFFERENTIALLY-COMPOUNDED GENERATOR—A compound generator in which the series field flux reduces the shunt field flux.

DYNAMOTOR—A special, highly efficient motor-generator set consisting of a common field and an armature with two or more windings, one to function as a motor, the others as generators.

EFFICIENCY—The ratio of the output to the input of a motor or generator.

ELECTROMAGNETIC INDUCTION—A voltage induced in a wire that is mechanically moved across a magnetic field.

EXCITER—A small, self-excited dc generator for the specific purpose of supplying field current for a large generator or motor.

FIELD RHEOSTAT—A two-terminal variable resistor connected in series with the field in shunt and compound motors and generators, or in parallel with the field in series motors and generators. The field rheostat controls the output of a generator and the speed of a motor.

FLAT-COMPOUNDED GENERATOR—A compound generator with the field coils designed to provide the same rated-load and no-load voltages.

GENERATOR—A device designed to produce electric energy from mechanical energy.

HYSTERESIS MOTOR—A type of synchronous motor in which the rotor is a solid steel cylinder.

INDUCTION MOTORS—AC motors which operate because of induced currents in their rotor windings.

INTERPOLES—See COMMUTATING POLES.

LINE CURRENT—The current in a power line or the current into or out of a motor or a generator.

LINE VOLTAGE—The voltage between two power lines or the voltage between two terminals of a generator or a motor.

MOTOR—A device designed to convert electric energy to mechanical energy.

NEUTRAL PLANE—See COMMUTATING PLANE.

IMPORTANT DEFINITIONS (Continued)

OVER-COMPOUNDED GENERATOR—A compound generator in which the field coils are designed to give a higher rated-load voltage than no-load voltage.

PHASE—A winding or branch circuit of an ac motor or generator forming part of polyphase load or source.

PHASE CURRENT—The current in a phase of a polyphase motor, generator or load.

PHASE VOLTAGE—The voltage across a phase of a polyphase motor, generator or load.

POLYPHASE—Having or producing two or more phases simultaneously.

PRINTED-CIRCUIT MOTOR—A dc motor using a printed-circuit armature.

REGULATION—In a generator, the ratio of the difference between the no-load and full-load voltages to the full-load voltage. For a motor, the ratio of the difference between the no-load and full-load speeds to the full-load speed.

ROTOR—The moving or rotating part of a motor or generator.

SELF-EXCITED GENERATORS—Generators which provide their own field coil current.

SEPARATELY-EXCITED—A generator or a motor which requires an exciter to provide the field coil current.

SERIES GENERATOR—A generator in which the field coils are connected in series with the armature and load.

SERIES MOTOR—A motor in which the field coils are connected in series with the armature and load.

SHADED-POLE MOTOR—A single-phase induction motor with a squirrel-cage rotor which has shading coils on the field pole tips to facilitate starting. The shading coils are uninsulated, permanently short-circuited auxiliary windings offset in magnetic position from the main winding.

SHADING COILS—Small short-circuited coils on one part of the tips of the field poles of an induction motor.

SHUNT GENERATOR—A generator in which the field coils are connected in parallel with or across the armature.

IMPORTANT DEFINITIONS (Continued)

SHUNT MOTOR—A motor in which the field coils are connected in parallel with or across the armature.

SIMPLEX WINDING—A complete armature loop winding, traced from a commutator segment, through all of the conductors in the armature winding, back to the commutator segment.

SLIP—The difference between the synchronous speed and the speed at which the motor rotor is rotating.

SLOT RIPPLE—In a generator output voltage, ripple caused by interruptions of the magnetic flux when a slot passes the pole piece.

SPLIT-PHASE MOTOR—A single-phase induction motor that uses the inductance of the starting winding to produce a rotating magnetic field for starting.

SQUIRREL-CAGE ROTOR—An ac motor rotor that employs copper bars embedded in the iron core and connected together by end rings.

STATOR—The stationary part of a motor or a generator.

SYNCHRONOUS GENERATOR—AC generators or alternators.

SYNCHRONOUS MOTOR—An ac motor that runs in exact step with the applied voltage. It has no slip.

TORQUE—Any force that tends to cause rotation.

UNDER-COMPOUNDED GENERATOR—A compound generator with the field coils designed to provide a lower rated-load voltage than no-load voltage.

Y CONNECTION—The connection of a three-phase system so that the phases form a Y.

ESSENTIAL SYMBOLS AND EQUATIONS

E	Voltage in volts
E_F	Rated full-load voltage
E_N	No-load voltage
f	Frequency in hertz or cycles per second
I	Current in amperes
P	Total number of field poles
P_T	True power in watts
pF	Power factor $= \cos \theta$
rpm	Speed in revolutions per minute
S	Slip in percent of synchronous speed
S_N	No-load speed (rpm)
S_R	Rated full-load speed (rpm)
sr	Rotor speed in revolutions per minute
ss	Synchronous speed in revolutions per minute
θ	Phase angle between the current and voltage

$$\text{Percent Regulation} = \frac{E_N - E_F}{E_F} \times 100 \tag{1}$$

$$\text{Percent Regulation} = \frac{S_N - S_R}{S_R} \times 100 \tag{2}$$

$$\text{Percent Efficiency} = \frac{\text{output}}{\text{input}} \times 100 \tag{3}$$

$$\text{Percent Efficiency} = \frac{\text{input} - \text{losses}}{\text{input}} \times 100 \tag{4}$$

$$f = \frac{P}{2} \times \frac{\text{rpm}}{60} = \frac{P \times \text{rpm}}{120} \tag{5}$$

ESSENTIAL SYMBOLS AND EQUATIONS (Continued)

$$P = \frac{120f}{rpm} \tag{6}$$

$$rpm = \frac{120f}{P} \tag{7}$$

$$S = \frac{ss - sr}{ss} \times 100 \tag{8}$$

$$P_T = I \times E \times pF \tag{9}$$

$$P_T = .576 \times I \times E \times pF \tag{10}$$

$$\%\ \text{Eff.} = \frac{\text{output}}{\text{input}} \times 100 \tag{11}$$

$$\%\ \text{Eff.} = \frac{\text{input} - \text{losses}}{\text{input}} \times 100 \tag{12}$$

$$\%\ \text{Eff.} = \frac{\text{output}}{\text{output} + \text{losses}} \times 100 \tag{13}$$

PRACTICE EXERCISE SOLUTIONS

1. True—While this is not a practical generator, it does operate on the principle of electromagnetic induction.

2. (b) north pole to a south pole.

3. (c) upon the directions of both flux and wire movement.—As illustrated by the left-hand rule, the direction of wire movement and flux must be known to determine current direction.

4. (b) commutator.

5. A multi-loop generator provides a smoother dc output.—The more loops a dc generator has, the smaller the variations in its output will be.

6. True—In a generator with closed-circuit windings, the windings are connected in series. As the voltage in one winding decreases, the voltage in another increases to maintain a constant output.

7. The armature slots, the commutator and the brushes.

8. A cumulatively-compounded generator.

9. (b) in parallel with the field winding.

10. (a) in series with the field winding.

11. (c) wire movement.

12. (b) magnetic flux.

13. To reverse the current in the armature loop so the reactance of the flux of the field and armature will continue to turn the armature in the same direction.

14. True—Counter emf is the result of electromagnetic induction. The left-hand rule shows that it opposes the supply voltage.

15. (b) larger.—The counter emf increases as the armature cuts the field flux at a faster rate.

16. (a) decreases.—Counter emf opposes the supply voltage, lowering the effective voltage which causes armature current.

17. (a) the same direction.—All the torques produced by each armature winding aid in turning the armature in the same direction.

PRACTICE EXERCISE SOLUTIONS (Continued)

18. Shunt motor.—Speed remains relatively constant with a change in load in a shunt motor.

19. True—A decrease in load causes armature speed and counter emf to increase. Armature current decreases, lowering the field current and flux which will allow the motor to speed up more. This process could continue if the load continually decreases until the motor actually destroys itself.

20. (a) maximum.—The resistance must be high to limit armature current to a safe value until the counter emf develops.

21. True

22. True

23. (b) armature reaction.

24. False—In the neutral plane the coil sides move parallel to the field flux, which results in minimum induction.

25. True

26. False—They should be in the neutral plane for minimum commutation.

27. 8.7%.

$$\text{Percent Regulation} = \frac{E_N - E_F}{E_F} \times 100$$

$$= \frac{250 - 230}{230} \times 100$$

$$= \frac{20}{230} \times 100 = \text{Approx. } 8.7\%$$

28. 80%.

$$1 \text{ HP} = 746 \text{ watts; } 1/2 \text{ HP} = \frac{746}{2} = 373 \text{ watts}$$

$$\text{input} = E \times I = 120 \times 3.88 = 465.6 \text{ watts}$$

$$\text{Percent Efficiency} = \frac{\text{output}}{\text{input}} \times 100 = \frac{373}{465.6} = \text{Approx. } 80\%$$

29. (b) collector rings.—Commutator segments are used in dc generators.

PRACTICE EXERCISE SOLUTIONS (Continued)

30. False—Because the output of an alternator is ac, the rotating loop connections to the external circuit do not have to be changed.

31. (b) flux.

32. True

33. (a) each mechanical revolution.

34. 60 Hz.—$f = \frac{P \times rpm}{120} = \frac{4 \times 1800}{120} = \frac{7200}{120} = 60$ Hz.

35. 12 poles.—$P = \frac{120f}{rpm} = \frac{120 \times 400}{4000} = \frac{48{,}000}{4000} = 12$ poles.

36. (b) smooth direct current.—The polarity of the magnetic poles must not change. Thus, rippleless direct current must be used.

37. (b) stator.

38. False—The voltage in one phase is maximum while the voltage in the other phase is minimum.

39. (a) 120° apart.—This is the result of the positioning of the armature windings.

40. True

41. (b) 1.73 times the current in one phase.—Current in one line is caused by the current in two phases. Because the phase currents are out-of-phase, they must be added vectorially. One line current is 1.73 times one phase current.

42. False—The line voltage is 1.73 times the phase voltage.

43. True

44. True

45. (a) torque increases.—Torque increases because the lag angle of the motor increases. This permits more current through the armature.

46. (b) are stationary, but because of a polyphase connection produce a magnetic field that rotates.

47. (c) is a steel cylinder.

PRACTICE EXERCISE SOLUTIONS (Continued)

48. **6000 rpm.—rpm** $= \frac{120f}{P} = \frac{120 \times 400}{8} = \frac{48{,}000}{8} = 6000.$

49. **False—An induction motor does not have armature coils.**

50. **The induced current in the rotor lags the rotating field because an induction motor depends upon flux cutting for its operation. If the rotor were turning at the same speed as the revolving field, no torque would be produced. The load and the friction of the motor keep the rotor lagging the field.**

51. **True—One set of windings is used only for starting purposes. After the motor has reached a certain speed, a centrifugal switch disconnects it from the supply and the motor operates as a single-phase motor.**

52. **False—The direction in which an induction motor rotor turns depends on the relation of the stator and the rotor magnetic fields. If one field is reversed with respect to the other, rotor rotation reverses.**

53. **(b) commutator segments.—A universal motor is simply a series-wound dc motor that also operates on ac.**

54. $P_T = 1.73 \times I \times E \times pF$

    $P_T = 1.73 \times 15 \times 220 \times .8$

    $P_T = 4567$ **watts.**

55. **84.8%.**

    1 HP = 746 watts

    $P_O = 746 \times 4.5 = 3357$ **watts**

    $P_{IN} = E \times I \times pF$

    $P_{IN} = 220 \times 20 \times .9 = 3960$ **watts**

    $\% \text{ Eff.} = \frac{3357}{3960} \times 100 =$ **Approx. 84.8%**

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7435A
EXAMINATION CHECK SHEET

1. D - A GENERATOR WHICH MUST KEEP OUTPUT RIPPLE TO A MINIMUM SHOULD USE -- MANY ARMATURE LOOPS AND COMMUTATING SEGMENTS.
Increasing the number of commutator segments increases the number of times that the induced voltage reaches maximum for every 360 electrical degrees of armature current. The increased number of peaks reduces the ripple.

2. D - ELECTRIC GENERATORS OPERATE ON THE PRINCIPLE OF -- ELECTROMAGNETIC INDUCTION.
When a wire is mechanically moved across a magnetic field, cutting the lines of flux, a voltage is induced in the wire. This principle is called "electromagnetic induction."

3. A - THE SPEED OF A MOTOR IS USUALLY CONTROLLED BY VARYING THE -- FIELD CURRENT.
Motor speed varies inversely with field flux, which results from the field current. Increasing the field current causes the motor to operate slower and vice versa.

4. A - WHEN A LOAD IS APPLIED TO A DC GENERATOR, THE NEUTRAL PLANE SHIFTS -- IN THE DIRECTION OF ARMATURE ROTATION.
In motors, the neutral plane shifts in the direction opposite to armature rotation.

5. B - THE MECHANICAL SWITCH THAT CONVERTS ALTERNATING CURRENT IN A GENERATOR LOOP TO DIRECT CURRENT IN THE LOAD IS KNOWN AS -- A COMMUTATOR.
The commutator segments slide past the brushes. When one commutator segment contacts a brush, current exists from the brush to the commutator segment. When that commutator segment contacts the next brush, current now is from the commutator segment to the other brush. Because the brushes don't move current through them, it is always in the same direction. Consequently, there is an alternating current in the armature loop and a direct current through the brushes and the load.

6. C - THE CURRENT IN ANY ONE LINE WIRE FROM AN ALTERNATOR WITH A DELTA-CONNECTED ARMATURE IS -- 1.73 TIMES THE PHASE CURRENT.
In a delta-connected alternator, the positions of the armature coils cause the currents to differ in phase by 120°; therefore, the currents cannot be added arithmetically. Consequently, the currents must be added vectorially. As a result, the current in any one line wire is 1.73 times the current in one phase. The phase current is 1/1.73 or .576 times the line current.

7. C - A MOTOR WHICH HAS A SHORT-CIRCUITED TURN OF COPPER AROUND A FIELD POLE TO PRODUCE STARTING TORQUE IS A -- SHADED-POLE MOTOR.
A shaded-pole motor uses extra field pole windings, called shading coils, to obtain a phase shift for starting small motors. The shading coils are actually made up of one short-circuited turn of copper around each field pole.

8. C - AN INDUCTION MOTOR THAT STARTS AS A TWO-PHASE MOTOR AND OPERATES AS A SINGLE-PHASE MOTOR IS CALLED -- A SPLIT-PHASE MOTOR.
A split-phase motor is a single-phase induction motor equipped with an auxiliary winding, displaced in magnetic position from and connected in parallel with the main winding. There is usually a switch that disconnects the auxiliary winding when the motor reaches a predetermined speed.

9. B - BY HOW MANY DEGREES DO THE VOLTAGES OF A THREE-PHASE ALTERNATOR DIFFER? -- 120°.
The number of degrees between the peaks of the voltages in a polyphase system is equal to 360°/N; where N is the number of phases. In a three-phase system there is 360°/3 or 120° between the phases.

10. B - FOR ONE MECHANICAL REVOLUTION OF THE ALTERNATOR IN FIGURE 2-3, MAXIMUM OUTPUT OCCURS -- FOUR TIMES.
For each mechanical revolution, each loop segment passes four poles, which produces four peaks in the voltage induced in that loop segment.

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QUESTIONS

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Indicate your answer on this sheet by filling in the box for the most correct answer to each question, as illustrated in the example below.

When all questions have been answered, place the answer card in the proper position to line up the boxes on the card with the boxes on the sheet.

Next, copy the complete lesson code into the space provided on the card, and fill in the answer boxes to correspond with those previously filled in on this sheet.

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LESSON CODE
7435A

Example: The purpose of a fan is to
A ☐ B ☐ C ■ D ☐
(A) pick apples. (B) make ice cubes. (C) move air. (D) cut paper.

1. A ☐ B ☐ C ☐ D ☒ **A generator which must keep output ripple to a minimum should use**
(A) many turns in two armature slots. (B) a series-field winding. (C) a shunt-field winding. (D) many armature loops and commutating segments.

2. A ☐ B ☐ C ☐ D ☒ **Electric generators operate on the principle of**
(A) armature reaction. (B) counter emf. (C) motor effect. (D) electromagnetic induction.

3. A ☒ B ☐ C ☐ D ☐ **The speed of a motor is usually controlled by varying the**
(A) field current. (B) armature current. (C) armature voltage. (D) interpole voltage.

4. A ☒ B ☐ C ☐ D ☐ **When a load is applied to a dc generator, the neutral plane shifts**
(A) in the direction of armature rotation. (B) toward an S pole of the field. (C) toward an N pole of the field. (D) in a direction opposite to that of armature rotation.

5. A ☐ B ☒ C ☐ D ☐ **The mechanical switch that converts alternating current in a generator loop to direct current in the load is known as**
(A) an armature. (B) a commutator. (C) a rotor. (D) a field.

6. A ☐ B ☐ C ☒ D ☐ **The current in any one line wire from an alternator with a DELTA-CONNECTED armature is**
(A) .576 times the phase current. (B) 1 ÷ 1.73 times the phase current. (C) 1.73 times the phase current. (D) the same as the phase current.

7. A ☐ B ☐ C ☒ D ☐ **A motor which has a short-circuited turn of copper around a field pole to produce starting torque is a**
(A) split-phase motor. (B) capacitor motor. (C) shaded-pole motor. (D) capacitor-start motor.

8. A ☐ B ☐ C ☒ D ☐ **An induction motor that STARTS as a TWO-PHASE motor and operates as a single-phase motor is called a**
(A) universal motor. (B) single-phase induction motor. (C) split-phase motor. (D) compound motor.

9. A ☐ B ☒ C ☐ D ☐ **By how many degrees do the voltages of a three-phase alternator differ?**
(A) 60°. (B) 120°. (C) 90°. (D) 180°.

10. A ☐ B ☒ C ☐ D ☐ **For one mechanical revolution of the alternator in Figure 2-3, maximum output occurs**
(A) two times. (B) four times. (C) once. (D) six times.

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POWER TRANSFER AND IMPEDANCE MATCHING

7440

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Most modern Hi-Fi Stereo systems employ a special power amplifier circuit that eliminates the need for a speaker impedance matching transformer.

Courtesy RCA, Consumer Electronics

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He that succeeds makes an important thing of the immediate task.

—Selected

POWER TRANSFER AND IMPEDANCE MATCHING

Most electronic devices and circuits are designed to work best with certain values of load impedance. If the load does not have the desired impedance value, **IMPEDANCE MATCHING** or **IMPEDANCE TRANSFORMING** devices may be used to transform the load impedance to the desired value. Common impedance matching devices include transformers, resistor networks, tuned circuits and sections of transmission line. Tube and transistor circuits may also be used for impedance matching.

The condition that exists when the load impedance does not have the desired value is called a **MISMATCH.** Some of the undesirable results of a mismatch are: distortion, reduced frequency response, loss of efficiency and less than the desired degree of power transfer from the source to the load.

SOURCES AND LOADS

Common sources of electric energy include batteries, generators, phono pickups and microphones. In some cases, amplifiers, oscillators and other circuits may also be viewed as sources of electric energy. A load is the device or circuit which uses the energy produced by the source. Common loads include speakers, antennas and amplifier input circuits. The load impedance may be either resistive, reactive or some combination of the two. Usually, however, the load impedance is basically resistive and impedance transforming devices are used to increase or decrease the resistance presented to the source.

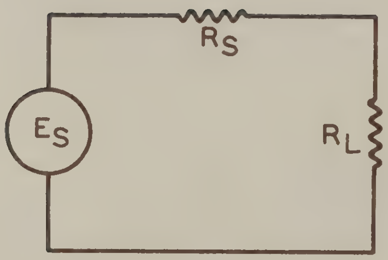


Figure 1

To see how the load impedance affects a circuit, let's examine a typical electric circuit. Most circuits can be simplified to a source, a load and conductors which connect the load to the source. Figure 1 is the schematic diagram of a circuit simplified in this way. E_S represents the source voltage, R_S represents the resistance of the source and R_L represents a resistive load. In Figure 1, the source is represented by a voltage generator. Common sources which may be represented in this way include: vacuum tubes, transistors, and ceramic microphones and pickups.

The voltage developed across a resistance is directly proportional to the resistance if the current through it is held constant. Voltage sources often have a high internal impedance. Thus, if the load impedance of Figure 1 is small, most of the source voltage appears across the internal impedance of the source. Very little source voltage appears across the load. However, as the load impedance is increased, more of the source voltage is developed across the load and less appears across R_S, the internal impedance.

To develop a *large* voltage across the load resistance of Figure 1, R_L should be many times *greater* than R_S. If the resistance of the device used as the load is too small, an impedance transforming device can be used to increase the resistance to the desired value.

Figure 2 shows another type of circuit. R_S represents the resistance of the source, and R_L represents a resistive load. The source I_S is represented by a current generator. Common sources which may be represented in this way include dynamic microphones, electromagnetic phono pickups and some transistor circuits. Current sources of this type often have a very low internal impedance.

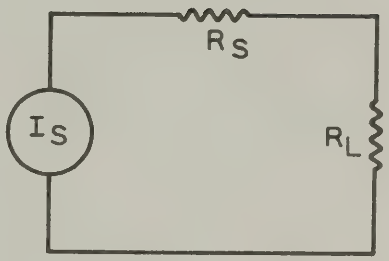


Figure 2

In the circuit of Figure 2, the circuit current depends on the total circuit resistance. The value of R_L must be low in order for the source to generate a usable amount of current. If the resistance of the load device is too high, an impedance transforming device can be used to decrease the resistance to the desired value.

The load impedance can be transformed to a different value while the power remains constant. Power is equal to the product of voltage and current. Thus, a high voltage and a low current can give the same power as a low voltage and a high current. However, impedance is equal to the ratio between voltage and current. A high voltage and a low current indicates a high impedance, and a low voltage and a high current indicates a low impedance.

Source and Load Impedances

Manufacturers specify optimum loads for many types of sources such as microphones and phono pickups. Some typical source impedances and recommended load impedances are as follows: A ceramic microphone may have an impedance of 250K ohms and a recommended load impedance of from 1 to 5 megohms. A dynamic microphone, on the other hand, has a very low impedance, usually around 20 ohms.

Phono pickups have similar variations in impedance. Ceramic pickups have high impedances, around 500,000 ohms being typical. Electromagnetic pickups have low impedances, around 25 to 400 ohms.

A loudspeaker is a typical example of a load. The most common speaker impedance ratings are 3.2 and 8 ohms. Transformers are generally used to connect speakers to amplifier outputs. As explained later in the lesson, the transformer turns ratio is selected to present the desired load impedance to the amplifier output.

Figure 3 lists typical input and output impedances for the three basic types of small signal transistor circuits. The input impedance is the impedance "seen" by the source as it supplies power to the circuit. Figure 4 shows the relative input and output impedances for the corresponding tube circuits. The input and output impedances of the tube circuits vary over a wider range of values than do the impedances of the transistor circuits. Therefore, no values are given in Figure 4. The grounded collector and grounded plate circuits listed in Figures 3 and 4 are also called emitter and cathode followers, respectively.

CIRCUIT	INPUT	OUTPUT
GROUNDED EMITTER	500–1000 Ω	30K–50KΩ
GROUNDED BASE	30–150 Ω	300K–500KΩ
GROUNDED COLLECTOR	20K–500KΩ	50–1000 Ω

Figure 3

CIRCUIT	INPUT	OUTPUT
GROUNDED CATHODE	HIGH	MED HIGH
GROUNDED GRID	LOW	MED HIGH
GROUNDED PLATE	HIGH	LOW

Figure 4

Because of the differences in impedance characteristics, some amplifier circuits do not work well together in cascade arrangements. For example, referring to Figure 3, the output of a grounded emitter stage is a poor match to the input of a grounded base stage. On the other hand, the input and output impedances of a grounded collector transistor circuit closely match the respective output and input impedances of any of the other circuits. Therefore, a grounded collector transistor circuit can be used to match the output of a grounded base circuit to the input of a grounded emitter circuit. The output terminals of the grounded base circuit are connected to the input terminals of the grounded collector circuit, and the output terminals of the grounded collector circuit are connected to the input terminals of the grounded emitter circuit.

Although the output of a grounded emitter stage is only a fair match to the input of another grounded emitter stage, this combination is frequently used without an impedance matching device. The voltage and power gains obtainable from cascaded grounded emitter amplifiers more than make up for the losses in power transfer due to impedance mismatching.

Maximum Power Transfer

Maximum power is transferred from a source to a load when the load impedance equals the source impedance. To see why this is so, assume that the source voltage E_S of Figure 1 is 300 volts, the source resistance R_S is 100 ohms, and the load resistance R_L is variable from 0 to 300 ohms.

Figure 5 shows the power, P_L, dissipated by the load as R_L is varied from 0 to 300 ohms. R_L is plotted in the horizontal direction and P_L is plotted in the vertical direction. As an example of how the values for P_L are obtained, assume that R_L is adjusted to 100 ohms. The total resistance across the source of Figure 1 is $R_S + R_L = 200$ ohms.

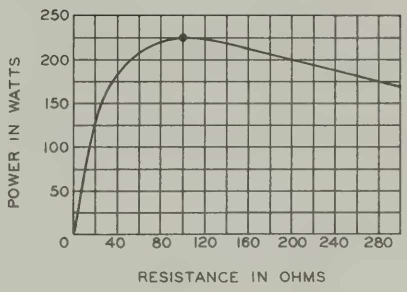


Figure 5

The circuit current is

$$\frac{E_S}{R_S + R_L} = \frac{300}{200} = 1.5 \text{ amperes}$$

and the power dissipated by R_L is $I^2R_L = (1.5)^2 \times 100 = 225$ watts.

The speaker shown above has a voice coil impedance of 8 ohms. Impedances of 8 and 16 ohms are typical values for modern Hi-Fi speakers.

Courtesy R. T. Bozak Mfg. Co.

From the graph of Figure 5, notice that maximum power is transferred from the source to the load when the load resistance is equal to the source resistance, 100 ohms, where the dot is on the curve. Thus, a load impedance equal to the source impedance provides maximum transfer of power.

IMPEDANCE MATCHING WITH TRANSFORMERS

The transformer is a common impedance transforming device. By choosing the proper turns ratio, the primary impedance can be made to match the source, while the secondary impedance matches the load.

For untuned audio-frequency transformers, the impedance measured across the primary can be found by multiplying the load impedance by the SQUARE of the turns ratio:

$$Z_P = \left(\frac{N_P}{N_S}\right)^2 Z_S \qquad (1)$$

where Z_P is the impedance measured across the primary, Z_S is the secondary or load impedance, N_P is the number of primary turns, and N_S is the number of secondary turns.

This equation can be rearranged to the form

$$\frac{Z_P}{Z_S} = \left(\frac{N_P}{N_S}\right)^2$$

which shows that the impedance ratio is equal to the square of the turns ratio. IF THE TURNS RATIO OF A TRANSFORMER IS 20/1, ITS IMPEDANCE RATIO IS $(20/1)^2$ OR 400/1.

One of the most common uses of transformers as impedance matching devices is at the output of an audio amplifier. Here, transformers are used to transform the impedance of the speaker to a higher value. To achieve the best compromise between power output, distortion and other characteristics, the load impedance connected to the output stage must be much higher than that provided by the average speaker. The load impedance of the output stage is the impedance seen by the stage as it looks at its load.

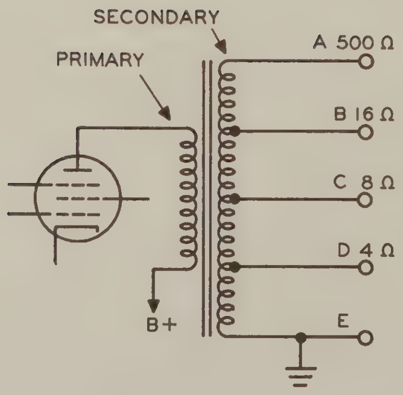


Figure 6

As shown in Figure 6, the secondaries of a high quality audio output transformer often contain a number of taps. These taps are used to transform a variety of impedances to the desired value. For example, a single speaker with a voice coil impedance of 8 ohms would be connected between points C and E. Two 8-ohm speakers connected in series present a total impedance of 16 ohms. Thus, two 8-ohm speakers could be connected in series between points B and E. Two 8-ohm speakers could also be connected in parallel between points D and E. (The equivalent impedance of two 8-ohm speakers connected in parallel is 4 ohms.)

More than two speakers can be connected in a series-parallel arrangement. The impedance of the combination may be calculated and the speaker leads connected to the taps that most nearly match the calculated impedance.

It is often necessary to locate a number of speakers over a wide area as in a theater. In systems of this type it is common to supply power to the speakers through a 500-600-ohm audio transmission line. The line may be connected between points A and E on the transformer of Figure 6. The speakers, in turn, are connected to the line through individual line matching transformers.

IMPEDANCE MATCHING WITH RESISTORS

Networks of fixed resistors provide another method of matching the impedances of a source and a load. The main disadvantage of using a resistor network in place of a transformer is the loss of power due to heating of the resistors.

In cases where the source impedance is higher than that of the load, the resistors can be connected as shown in Figure 7. Here, R_S represents the source resistance, R_L is the load resistance, and R_1 and R_2 are the respective series and shunt resistances of the impedance matching network. Since R_1 and R_2 form an inverted L in the schematic, the circuit is called an L NETWORK.

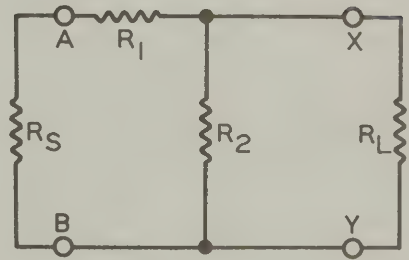


Figure 7

The total resistance across the input terminals A and B of the L network with R_S disconnected is equal to the sum of R_1 and the equivalent resistance of R_2 and R_L in parallel. Thus, in the form of an equation, the input resistance R_{IN} of the network is

$$R_{IN} = R_1 + \frac{R_2 R_L}{R_2 + R_L} \tag{2}$$

The output resistance between X and Y (with R_L disconnected) is equal to the equivalent resistance of R_2 in parallel with the series combination of R_1 and R_S. In the form of an equation,

$$R_{OUT} = \frac{R_2 (R_1 + R_S)}{R_2 + (R_1 + R_S)} \tag{3}$$

In cases when the load impedance is higher than that of the source, the L network is reversed. The shunt resistor, R_2, is connected across the source, and the series resistor, R_1, is connected in series with the load. The respective equations for the input and output resistances of such a network are

$$R_{IN} = \frac{R_2 (R_1 + R_L)}{R_2 + (R_1 + R_L)} \tag{4}$$

$$R_{OUT} = R_1 + \frac{R_2 R_S}{R_2 + R_S} \tag{5}$$

Besides matching input and output impedances, resistor networks are also used in circuits that require nearly constant input impedances. These networks reduce the variations in input impedance caused by variations in the external load impedance. Such networks are called **ISOLATION PADS.**

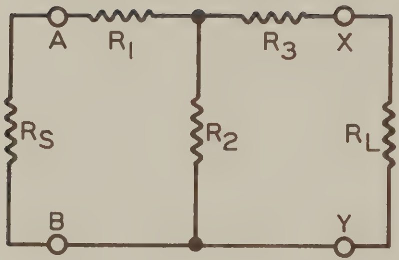


Figure 8

Figure 8 is the schematic diagram of one type of isolation pad. The isolation pad of Figure 8 is called a T NETWORK, since R_1, R_2 and R_3 are drawn in the form of a "T". R_S represents the source resistance, R_1 and R_3 the series resistance, R_2 the shunt resistance, and R_L the load resistance. The input resistance of the T network (with the source disconnected) can be found from the following equation:

$$R_{IN} = R_1 + \frac{R_2 (R_3 + R_L)}{R_2 + (R_3 + R_L)} \tag{6}$$

Let's see how such a network reduces variations in input resistance caused by variations in the load impedance. Assume that in the circuit of Figure 8 R_S is 500 ohms, R_1 and R_3 are each 409 ohms, R_2 is 101 ohms and R_L is 500 ohms. Substituting in Equation 6,

$$R_{IN} = 409 + \frac{101\ (409 + 500)}{101 + (409 + 500)} = 499.9 \text{ ohms.}$$

For one extreme case, assume that R_L is shorted. This reduces R_L to zero. Substituting in Equation 6,

$$R_{IN} = 409 + \frac{101\ (409 + 0)}{101 + (409 + 0)} = 490 \text{ ohms.}$$

For another extreme case, assume that the load is open or disconnected. This increases the value of R_L to infinity. In this case, the only complete circuit across the source is made up of R_1 and R_2 in series. The resulting input resistance is

$$R_{IN} = R_1 + R_2 = 409 + 101 = 510 \text{ ohms.}$$

Thus, changing the load resistance from zero to infinity (short or open) causes a change of only 20 ohms or 4% in the input resistance.

The following Practice Exercise questions cover the subjects which you have just studied. They are:

SOURCES AND LOADS

SOURCE AND LOAD IMPEDANCES

MAXIMUM POWER TRANSFER

IMPEDANCE MATCHING WITH TRANSFORMERS

1. A phono pickup is viewed as a (a) source, (b) load.

2. A triode voltage amplifier can be viewed as a generator with the source resistance in series with the generator and a load resistance connected across both the generator and the source resistance. Which of the following relationships will provide the greatest voltage across the load? (a) A load resistance less than the source resistance. (b) A load resistance equal to the source resistance. (c) A load resistance greater than the source resistance.

3. Which of the following types of microphones would most likely be connected to the input of an amplifier through a step-up transformer? (a) A ceramic microphone. (b) A dynamic microphone.

4. Ceramic phono pickups have (a) high impedances, (b) low impedances.

5. From an impedance matching standpoint, connecting the output of a grounded emitter transistor amplifier to the input of a grounded base transistor amplifier provides a (a) poor impedance match, (b) good impedance match.

6. What type of transistor amplifier configuration can be used to provide a good impedance match between any two other configurations?

7. To obtain maximum power transfer from a source to a load, the load impedance must be (a) equal to the source impedance, (b) twice the source impedance, (c) half the source impedance.

8. What type of impedance matching device is usually used to transform the impedance of a loudspeaker to the value required at the amplifier output?

9. The output stage of an audio amplifier requires a load impedance of 2500 ohms. What is the turns ratio of the transformer required to transform the impedance of a 4-ohm speaker to this value?

10. An audio output transformer has secondary taps labeled ground, 4 ohms, 8 ohms, 16 ohms and 500 ohms. Give two ways of properly connecting two 8-ohm speakers to this transformer.

Figure 9 shows the circuit of another type of isolation pad. This type of circuit is called a π NETWORK. Notice how the arrangement of resistors R_1, R_2 and R_3 resembles the Greek letter π. Here, shunt resistor R_2 is connected across the input terminals A and B, shunt resistor R_3 is connected across the output terminals X and Y, and series resistor R_1 is connected between terminals A and X. This type of network is often used where the input and output impedances are low.

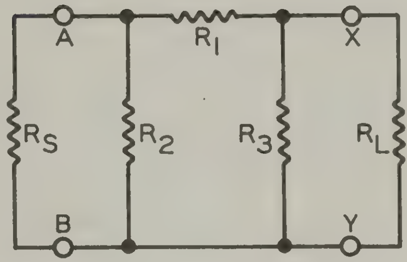


Figure 9

In the circuits of Figures 7 to 9, the series resistors are connected in only one side or line. Because the features of one side of the circuit differ from those of the other side, such a circuit is called an **UNBALANCED NETWORK.** In many cases, circuits are required that have equal series resistances in both sides or lines. These circuits are called **BALANCED NETWORKS.**

The circuits of Figures 7 to 9 can be changed to balanced networks by placing half the series resistance in the lower line. Thus, the series resistance R_1 of Figure 7 may be divided into two equal parts, $R_1/2$. These resistances are connected as shown in Figure 10, and the unbalanced L becomes a balanced U NETWORK. In the same way, by halving the series resistances, the unbalanced T of Figure 8 becomes the balanced H network of Figure 11. Still following the same plan, the unbalanced π of Figure 9 becomes the balanced O NETWORK of Figure 12.

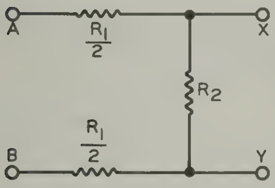


Figure 10

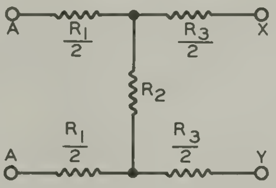


Figure 11

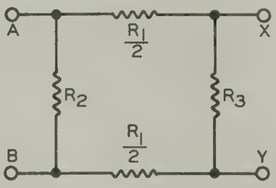


Figure 12

When the source and load impedances are reactive, the networks of Figures 7 through 12 may be made up of reactances, instead of resistances. The input and output impedances of such circuits are calculated in much the same way as for resistive networks. One difference between the input and output impedance calculations for the two circuits is that the phase angle for a reactive circuit may vary from 0° to ±90°, whereas the phase angle of a resistive network is always 0°. Another difference is that the input and output impedances vary with frequency in a reactive network. Reactive circuits of this type are often used as filters.

It is often necessary to transfer energy from a balanced line to an unbalanced line. The circuits and devices used to perform this task are called **BALUNS.** The term **BALUN** means BALanced to UNbalanced.

Let's take a look at a practical example of how resistors can be used for impedance matching and isolation. Assume that a number of television receivers are to be connected to the same antenna. Each television receiver has a balanced input impedance of 300 ohms. A transmission line carries the signal from the antenna to the receivers. The transmission line and antenna can be thought of as a source with an internal impedance of 300 ohms.

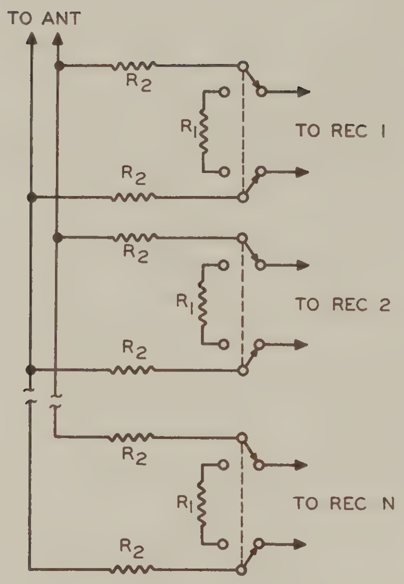


Figure 13

Figure 13 shows how resistors can be used to connect a number of receivers to a single transmission line. Resistors R_2 are placed in series with the receiver input terminals. These resistors in series with the receiver input terminals provide the proper load impedance for the transmission line.

Resistors R_1 are equal in value to the receiver input impedances. They are connected across the line when the receivers are disconnected. In the circuit of Figure 13, resistors R_1 are substituted for the receivers by means of double-pole double-throw switches. This circuit may be used when all receivers have the same input impedance, and this impedance is equal to that of the transmission line.

The value of resistors R_2 may be found by using the following formula:

$$R_2 = \frac{R_1 (N - 1)}{2} \tag{7}$$

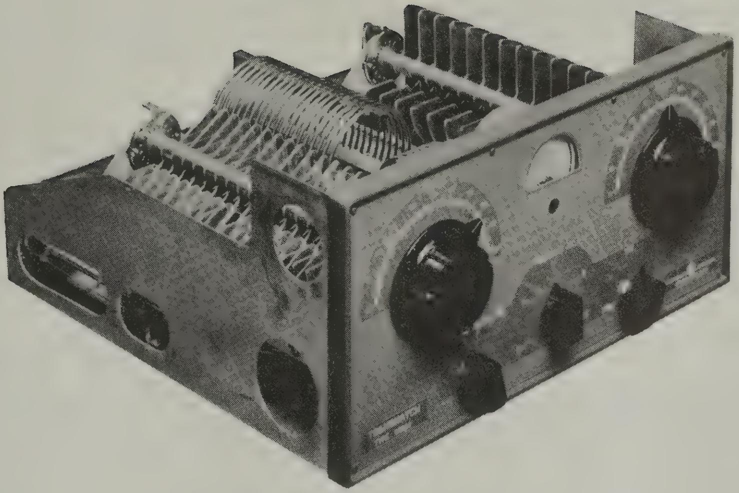
where R_1 is equal to the impedance of the transmission line and receiver inputs, and N is the number of receivers to be connected to the line.

To illustrate the use of this equation, assume that you want to connect two receivers to a single 300-ohm line. As explained before, the input impedance of each receiver is also 300 ohms. Substituting in Equation 7,

$$R_2 = \frac{300 (2 - 1)}{2} = 150 \text{ ohms.}$$

With R_2 equal to 150 ohms, the total resistance of the receiver 1 input circuit is 150 + 300 + 150, or 600 ohms. The total resistance of the receiver 2 input circuit is also 600 ohms. As far as the transmission line is concerned, the load resistance is 600/2, or 300 ohms. Thus, the load impedance matches the source impedance and maximum power will be delivered to the load.

The resistors in series with the receiver inputs produce signal losses. Because of these losses, not all of the signal available from the antenna is transferred to the receiver. These losses must be accepted when resistors are used in impedance matching and isolation networks.



The antenna tuner shown above is designed to add inductance or capacity to an antenna system so that the correct load impedance will be presented to the transmitter.
Courtesy James Millen Mfg. Co., Inc.

IMPEDANCE MATCHING WITH RESONANT CIRCUITS

Resonant circuits are also often used as impedance matching devices. Their most common uses are to transfer energy from one tube or transistor stage to another and to transfer energy from a radio transmitter to an antenna.

Figure 14 shows how a series LC circuit can be used to transform the resistance of a load to a smaller value. The input impedance is less than the impedance of the load. The load impedance is connected across the inductance, L, since the inductor is a high impedance. The reactance of capacitor C cancels that of the inductive portion of the parallel circuit at the frequency used. Thus, the input impedance, R_{IN}, is purely resistive and is smaller than the load resistance.

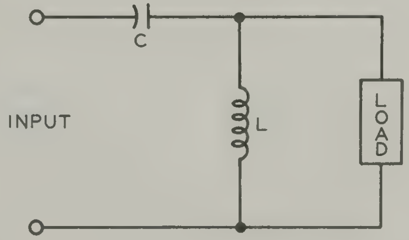


Figure 14

At resonance, the impedance of a parallel LC circuit is maximum, and is purely resistive. Figure 15 shows how a tapped coil can be used to provide the desired resistance to the source. The impedance between the tap and the lower terminal of the coil is less than that between the two end terminals of the coil. This matches a high impedance load to a low impedance source. Also, as shown in Figure 16, a tapped capacitance can be used to provide a similar impedance transformation.

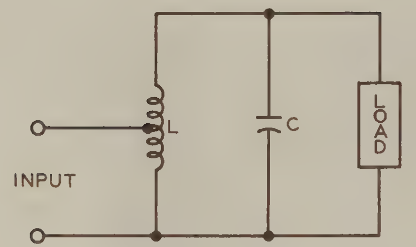


Figure 15

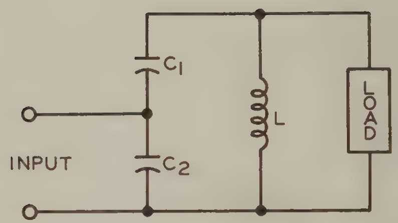


Figure 16

Figure 17 shows how a tapped coil can be used to match a low impedance load to a higher impedance source. When the load resistance has a very low value, it may be connected in series with the coil as shown in Figure 18. The load of Figure 18 may be the actual load or it may be reflected into the circuit by transformer action. Since L and C form an inverted L in the schematic, the circuit is called an L network.

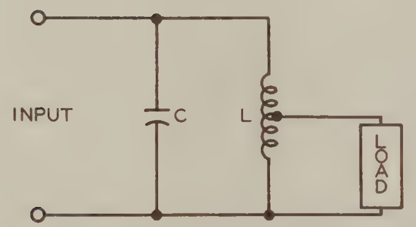


Figure 17

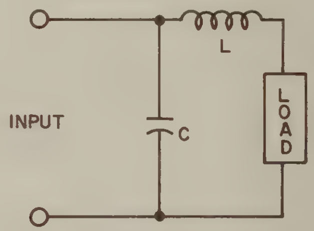


Figure 18

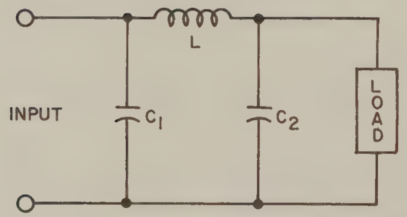


Figure 19

Figure 19 is the schematic diagram of a π network. This type of network is often used to couple the output of a transmitter to an antenna. The network is often used for low to medium input and output impedances. These impedances are generally between 50 to 500 ohms.

The LC_1 portion of the π network of Figure 19 forms an L network like that of Figure 18. However, in the π network, the load resistance is reduced in value by C_2 just as L reduces the impedance of the load in the circuit of Figure 14. Thus, the inductance, L, of Figure 19 must be somewhat greater than that of Figure 18 to cancel the capacitance provided by C_2. The π network has many advantages over the simple L network. One of the advantages is greater harmonic attenuation.

The following Practice Exercise questions cover the subjects which you have just studied. They are:

IMPEDANCE MATCHING WITH RESISTORS

IMPEDANCE MATCHING WITH RESONANT CIRCUITS

11. When an L-type network is used to match a low impedance source to a high impedance load as in Figure 14, the shunt arm of the network is connected across the (a) source, (b) load.

80

45 36

12. A certain L network is made up of a series resistance of 80 ohms and a shunt resistance of 45 ohms. If a load resistance of 36 ohms is connected across the shunt resistance, the input resistance of the network is (a) 100 ohms, (b) 50 ohms, (c) 25 ohms.

13. An isolation pad helps to prevent changes in load impedance from affecting the source. True or False?

14. The pad more likely to be used to isolate a balanced load from a balanced source would be (a) a T pad, (b) an H pad.

15. In the circuit of Figure 14, the load resistance is shunted by an inductor to lower the resistance presented to the source. What is the purpose of the capacitance in series with the source?

16. The impedance between the tap and the lower terminal of Figure 15 is (a) greater than the impedance between the two end terminals, (b) less than the impedance between the two end terminals.

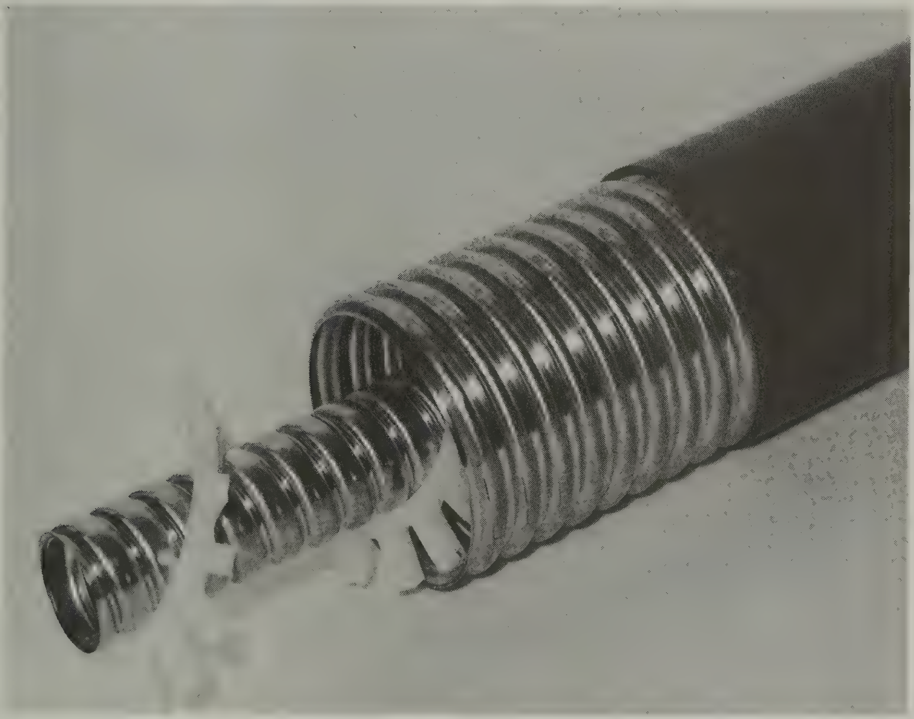
17. Placing the load resistance in series with an inductor in a parallel resonant circuit, as in Figure 18, causes the impedance presented to the source to (a) increase, (b) decrease, (c) remain the same.

18. In the π network of Figure 19, why must the value of L be greater than that required to form a resonant circuit with C_1 at the operating frequency?

TRANSMISSION LINES

A transmission line generally consists of two or more conductors used to transfer electric energy from one point to another. In transmitting dc energy and low-frequency ac energy, you can think of the transmitted energy in terms of the current in the conductors and the voltages between them. At radio frequencies, however, it is often simpler to think of the transmitted energy in terms of electromagnetic waves.

Transmission lines can be split into two classes—electrically long lines and electrically short lines. An electrically long line is one in which the physical length of the line is about equal to or longer than the wavelength of the transmitted frequency.



The photo above shows a cutaway view of a section of air dielectric coaxial cable.

Courtesy Andrew Corp.

The wavelength of the common 60-Hz power frequency is about 3100 miles. Therefore, power lines are thought of as electrically short. The wavelength of an audio frequency of 15,000 Hz is about 12.4 miles. Therefore, audio transmission lines, such as those used in public address systems and recording studios, are also electrically short. Telephone lines, on the other hand, because of their length are good examples of electrically long transmission lines. Radio frequency transmission lines, such as those used to connect an antenna to a transmitter or receiver, are almost always electrically long.

The resistance of a transmission line dissipates energy in the form of heat. Thus, not all of the energy applied to the line by a source reaches the load. For example, assume that a number of speakers are connected to a 500-ohm audio transmission line. Even though the speakers may have equal wattage ratings, those farthest from the source will receive less energy than those nearest the source due to the loss in the connecting lines.

Basic Types of Lines

Figure 20 shows two basic types of transmission lines. The transmission line of Figure 20A is made up of two parallel conductors. The spacing between the two parallel conductors is kept constant and the conductors are insulated from each other by an insulating material called the dielectric. This type of transmission line is often referred to as "TWIN LEAD." One variation of this construction consists of conductors separated at equal intervals by insulating spacers.

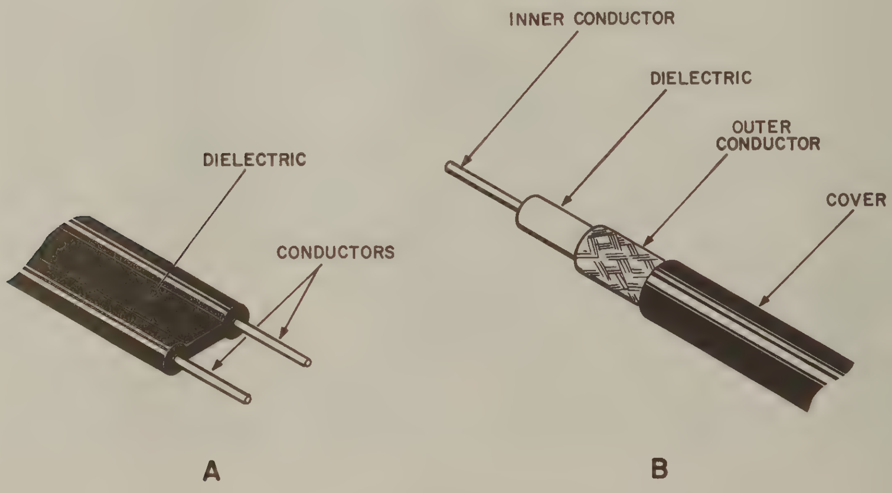


Figure 20

The transmission line of Figure 20B is called **COAXIAL CABLE.** In this type of line, a central conductor is mounted coaxially within a surrounding metallic covering. The central wire and the surrounding metallic covering form the two conductors of the line. The metallic covering may be flexible or rigid. The central conductor is held at the center of the outer conductor by means of a dielectric material, or by insulating spacers. The outer conductor confines the transmitted energy to the inside of the line. It also serves as a shield to prevent pickup of stray electromagnetic fields. As shown in Figure 20B, a coaxial cable may be protected by a weatherproof cover.

Line Constants

A changing magnetic field around a wire cuts the wire and induces a counter emf in it. Thus, the conductors of a transmission line have inductance. No material is a perfect conductor. Therefore, the conductors of a transmission line also have resistance. Since no material is a perfect insulator, the resistance between the conductors is less than infinite. A capacitor is made up of conductors separated by a dielectric. Thus, there is also capacitance between the conductors.

Since these properties are distributed throughout the length of the transmission line, they are called distributed constants. The inductance, resistance and capacitance of inductors, resistors and capacitors, respectively, are called lumped constants.

The properties of a transmission line may be stated in terms of a unit length of line. For example, a transmission line may have a capacitance of 30 picofarads per foot. Thus, as shown in Figure 21, a transmission line can be thought of as being made up of a series of unit lengths. Each unit length has a series inductance, a series resistance, a shunt resistance and a shunt capacitance.

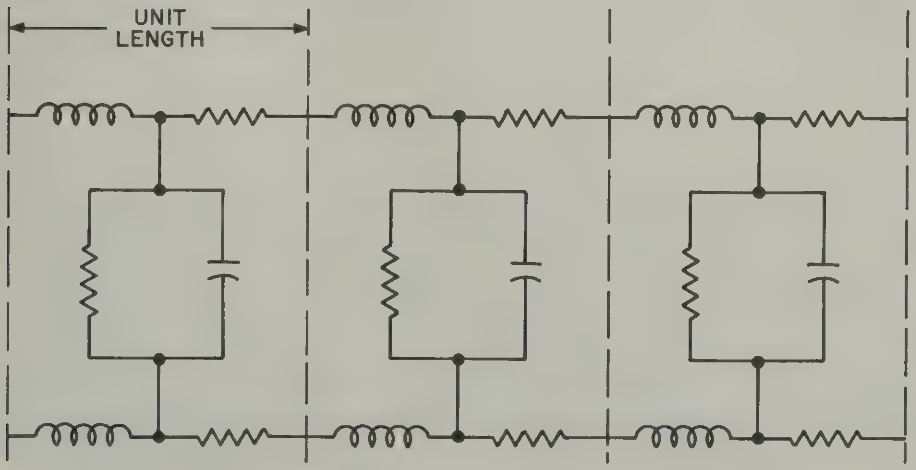


Figure 21

Characteristic Impedance

Each unit length of Figure 21 has a certain impedance. As additional unit lengths are added to the line, the line impedance is reduced. However, each added length has less effect on the resulting impedance than the previous length. The resulting impedance of an infinitely long line is called its **CHARACTERISTIC IMPEDANCE.** This is the impedance presented to a source by an infinitely long line.

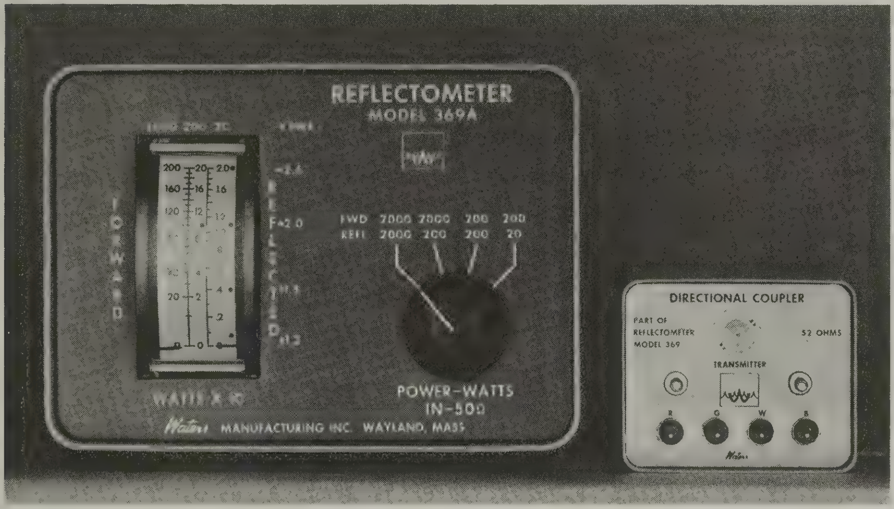
The value of the characteristic impedance depends on the inductance, resistance and capacitance characteristics of the line. In turn, these characteristics depend on the size and kind of wire, the nature of the dielectric separating the wires and the distance between the wires. Changes in any of these factors change the characteristic impedance. The characteristic impedance also varies slightly with frequency.

Line Termination

Although it is impossible to construct an infinitely long line, THE INPUT IMPEDANCE OF A LENGTH OF LINE TERMINATED IN ITS CHARACTERISTIC IMPEDANCE IS EQUAL TO THE CHARACTERISTIC IMPEDANCE. Terminating a length of line in its characteristic impedance is the same as connecting it to an infinitely long transmission line. The source now works into the characteristic impedance of the line, and the line losses are minimum.

A transmission line terminated in a load equal to its characteristic impedance is called a **NONRESONANT LINE.** The voltage and current in a nonresonant line are always in phase. In a nonresonant line all of the energy transmitted along the line is absorbed by the load, except for a small amount dissipated in the line.

A transmission line terminated in a load which is not equal to its characteristic impedance is called a **RESONANT LINE.** When the voltage and current waves reach the end of a resonant line, the energy is not absorbed completely by the load. Instead, some of the energy is reflected back toward the source. The values of voltage and current along a transmission line are equal to the algebraic sum of the transmitted and reflected waves. The transmitted and reflected waves move at the same speed, but in opposite directions. Due to the addition and subtraction of the two waves, at certain points along the line the voltage and current are minimum. Midway between these minimum points, the voltage and current alternately rise to maximum positive and negative values. Because they are out-of-phase, the voltage and current minimums do not occur at the same point. The same is true for the maximums. Since they do not move along the line, these variations in voltage and current are called **STANDING WAVES.**



The reflectometer shown above determines the SWR by measuring the forward and reflected power.
Courtesy Waters Manufacturing Inc.

Standing Wave Ratio

The ratio between maximum and minimum values of the standing waves is called the **STANDING WAVE RATIO.** The term standing wave ratio is abbreviated **SWR.** The SWR of a line can be expressed in the form of an equation as:

$$\mathrm{SWR} = \frac{E_{MAX}}{E_{MIN}} = \frac{I_{MAX}}{I_{MIN}} \qquad (8)$$

The SWR of a line is a measure of the degree of mismatch between the transmission line and its load. For example, if the line is terminated in its characteristic impedance, there are no standing waves and no maximum and minimum values of voltage and current. Or from another viewpoint, the maximum and minimum points along a nonresonant line have the same value. Referring to Equation 8, this gives an SWR of 1. This is the lowest possible SWR obtainable. The standing wave ratio is often expressed with respect to the perfect SWR of 1. For example, if the SWR is 2.5 it is often stated as 2.5:1 (read as 2.5 to 1).

The SWR can also be expressed in terms of the characteristic impedance Z_O and the load resistance R_L as follows:

$$\text{SWR} = \frac{Z_O}{R_L}, \text{ or } \frac{R_L}{Z_O} \tag{9}$$

Two forms of the equation are given so that the SWR may be expressed by a number greater than 1. To do this, the larger value is divided by the smaller value.

Line Sections

Assume that a section of transmission line is terminated in a short circuit, as shown in Figure 22A. No voltage can be developed across a short circuit, but the current through a short circuit is maximum. Thus, the voltage standing wave is minimum and the current standing wave is maximum at the shorted end.

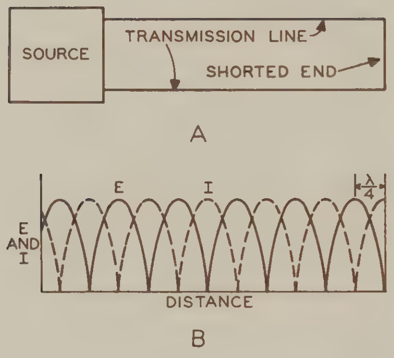


Figure 22

Figure 22B shows the voltage and current standing waves along the line. The voltage standing wave is represented by the solid line. The current standing wave is represented by the dashed line. Since we are only interested in maximum and minimum values, both the positive and negative alternations are drawn upward on the graph. The left edge of the graph indicates the voltage and current standing waves at the source. The right edge of the graph indicates the voltage and current at the shorted end. The voltage and current at the shorted end will remain the same, no matter how long the line. However, the voltage and current at the source will vary with the length of the line.

At any point along a transmission line, the impedance (Z) is equal to E/I. In a nonresonant line, the ratio of voltage to current is the same at all points. Therefore, E/I is a constant equal to the characteristic impedance at all points along the nonresonant line.

On the other hand, in a resonant line the ratio E/I varies from point to point along the line. Therefore, the line impedance of the resonant line also varies. For example, referring to Figure 22B, E is minimum and I is maximum at the shorted end. THEREFORE, THE IMPEDANCE AT THE SHORTED END IS MINIMUM. However, at a point located one-quarter wavelength ($\lambda/4$) back from the shorted end, E is maximum and I is minimum. Since maximum voltage and minimum current are characteristics of a high impedance, the impedance at this point is maximum.

Figure 23A shows a section of transmission line terminated in an open circuit. Figure 23B shows the voltage and current standing waves along the line. The current standing wave is minimum at the open end and the voltage standing wave is maximum. Thus, the impedance is maximum at the open end of a transmission line. At a point one-quarter wavelength back from the open end, E is minimum and I is maximum. Thus, $E/I = Z$ is minimum at this point.

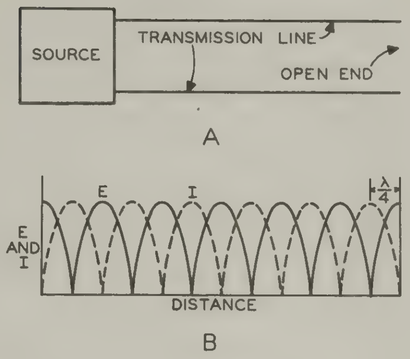


Figure 23

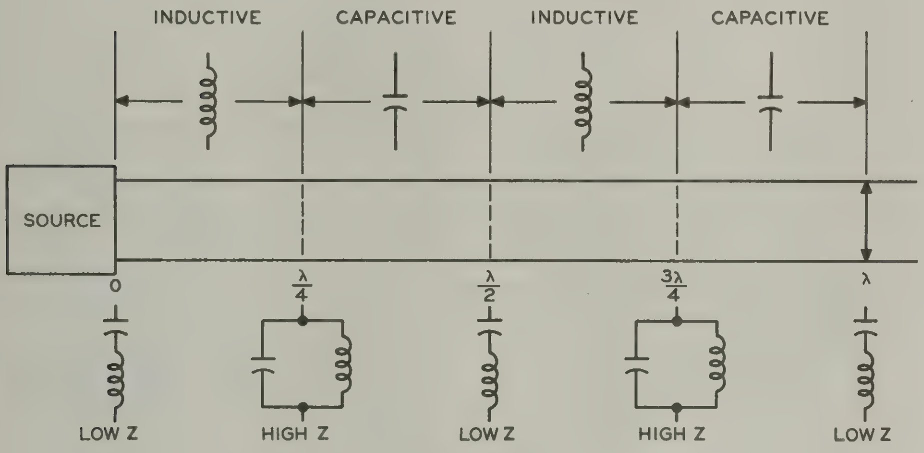


Figure 24

Figures 24 and 25 show how the input impedance of both a shorted and open line varies with length. The double-arrowed vertical line of Figure 24 is a movable shorting bar. The bar may be moved back and forth along the line to vary its effective length.

Assume that the shorting bar is moved from the source to the λ/4 (one-quarter wavelength) point. To the source, the line acts or looks like an inductive reactance of increasing magnitude as the shorting bar is being moved. In Figure 24, this is illustrated by the coil symbol above the transmission line between 0 and λ/4. AT EXACTLY ONE-QUARTER WAVELENGTH (λ/4) from the source, the line acts like a very high impedance, or a PARALLEL RESONANT CIRCUIT. This is indicated below the line at λ/4. Moving toward λ/2 from λ/4, the line acts like a capacitive reactance of decreasing magnitude. AT EXACTLY ONE-HALF WAVELENGTH (λ/2), the line acts like a SERIES RESONANT CIRCUIT or a low impedance to the source.

Between λ/2 and 3λ/4 the line again acts like an inductive reactance of increasing magnitude to the source. AT EXACTLY 3λ/4 it again acts like a PARALLEL RESONANT CIRCUIT to the source. Moving from 3λ/4 to λ it again presents a decreasing capacitive reactance to the source. AT EXACTLY λ it is again equivalent to a SERIES RESONANT CIRCUIT, presenting a very low impedance to the source.

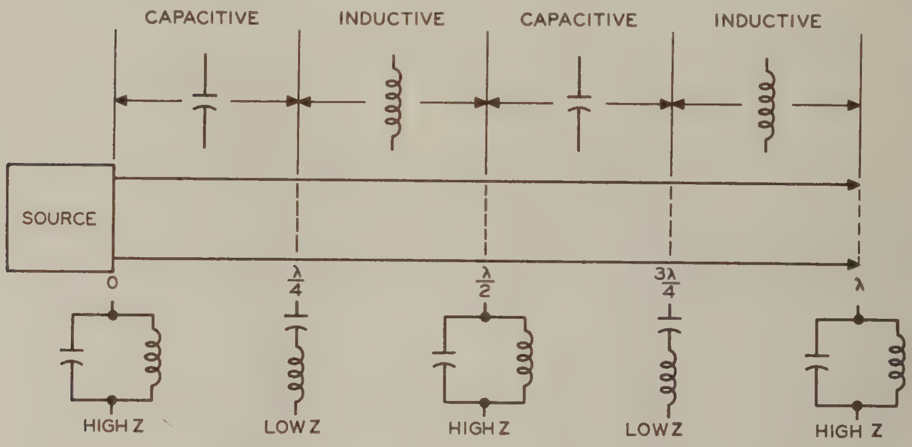
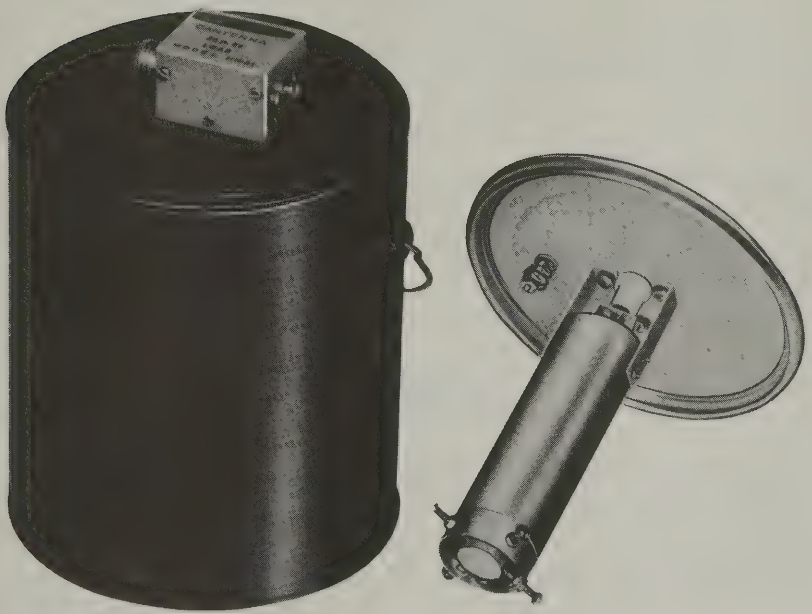


Figure 25

The line of Figure 25 is terminated in an open circuit. The variations in impedance along an open-circuited line are opposite to those along a short-circuited line. As the length of the open-circuited line is increased from 0 to λ/4, it presents a decreasing capacitive reactance to the source. At exactly λ/4, the line acts like a series resonant circuit presenting a very low impedance to the source.

From λ/4 to λ/2, an increasing inductive reactance is presented to the source. At exactly λ/2, the line acts like a parallel resonant circuit. A decreasing capacitive reactance is presented to the source from λ/2 to 3λ/4. At 3λ/4 the line again acts like a series resonant circuit. From 3λ/4 to λ, the line again acts like an increasing inductive reactance to the source. At λ it is again equivalent to a parallel resonant circuit.

Different lengths or sections of transmission line are often used as circuit elements in electronic equipment. Various values of inductance and capacitance and both series and parallel resonant circuits are obtained by choosing a line of suitable length as explained for Figures 24 and 25. These line sections are most useful at higher frequencies (VHF and UHF) where the required values of inductance and capacitance are too small to be provided by ordinary components. Furthermore, the Q's of transmission line sections are much higher than those of ordinary circuit components. These sections could be employed in lower frequency circuits also, but are impractical because of the excessive lengths required.



The device shown above is referred to as a "Dummy Load." It is a special noninductive 50-ohm resistor which is used in place of the regular antenna during radio transmitter tests and adjustments.

Courtesy Heath Co.

Impedance Matching with Line Sections

In many ways, a one-quarter wavelength section of transmission line acts like a transformer. For example, referring to Figures 24 and 25, although a one-quarter wavelength section may be terminated in a short circuit, it presents a high impedance to the source. A one-quarter wavelength section terminated in an open circuit presents a low impedance to the source. The relationship between the load impedance and the input impedance of a quarter-wave section is given by the equation

$$Z_{IN} = \frac{Z_O^2}{Z_{OUT}} \tag{10}$$

where Z_{IN} is the impedance looking into the line,
Z_{OUT} is the impedance of the load, and
Z_O is the characteristic impedance of the line.

Equation 10 can be rearranged to the following form:

$$Z_O = \sqrt{Z_{IN} \times Z_{OUT}} \tag{10a}$$

This form of the equation can be used to match two given impedances, such as a source and a load. This can be done by connecting the two impedances together with a quarter-wave transmission line having a characteristic impedance equal to the square root of their product.

SUMMARY

Most electronic devices and circuits work best with certain values of load impedance. If the load impedance is not the desired value, an impedance matching or transforming device may be used to transform the load impedance to the desired value.

A mismatch between the source and the load may result in distortion, reduced frequency response, loss of efficiency and less than the desired degree of power transfer. Maximum power is transferred from the source to the load when the impedance of the load matches that of the source. This value of load impedance, however, may not be the best value for other desirable characteristics. The best value of load impedance is often chosen as a compromise of many characteristics.

Common impedance transforming devices include transformers, resistor networks, resonant circuits and sections of transmission line. Common tube and transistor circuits used for impedance matching include the cathode follower and emitter follower (grounded plate and grounded collector).

A transmission line consists of two or more conductors used to transfer electric energy from one point to another. The characteristic impedance of a transmission line is equal to the input impedance of that line if it were infinitely long. The characteristic impedance of a transmission line depends

The following Practice Exercise questions cover the subjects which you have just studied. They are:

TRANSMISSION LINES

BASIC TYPES OF LINES

LINE CONSTANTS

CHARACTERISTIC IMPEDANCE

LINE TERMINATION

STANDING WAVE RATIO

LINE SECTIONS

IMPEDANCE MATCHING WITH LINE SECTIONS

19. Briefly describe the physical makeup of coaxial transmission line.

20. If the two wires of a parallel two-wire transmission line are moved farther apart, what is the effect on the characteristic impedance of the line?

21. What effect does the length of a transmission line have on its characteristic impedance?

22. What is the phase relation between the current and voltage in a nonresonant transmission line?

23. What type of termination produces a nonresonant transmission line?

24. Standing waves are present on (a) resonant transmission lines, (b) nonresonant transmission lines.

25. If the maximum amplitude of a standing wave is three times the minimum amplitude of the wave, what is the standing wave ratio of the line?

26. If the degree of mismatch between a transmission line and its load is increased, the SWR (a) increases, (b) decreases, (c) remains the same.

27. What is the standing wave ratio of a transmission line terminated in its characteristic impedance?

28. To the source, a shorted length of transmission line ¼ wavelength long acts like a (a) series resonant circuit, (b) parallel resonant circuit.

29. Assume that a 1/4 wavelength line having a characteristic impedance of 500 ohms is terminated in a resistive load of 75 ohms. What is the impedance looking into the line?

30. Assume that a 1/4 wavelength line is used to match a 500-ohm line to a 72-ohm antenna. What is the required characteristic impedance of the matching line?

300) = 75 X

500

75

36000

on the physical characteristics of the line. If a length of line is terminated in its characteristic impedance, its input impedance is equal to the characteristic impedance.

If a transmission line is terminated in its characteristic impedance, all of the transmitted energy is absorbed by the load. If the load impedance is not equal to the characteristic impedance of the line, some of the energy is reflected back to the source. This results in standing waves of voltage and current along the line. The ratio between the maximum and minimum values of the voltage or current standing waves is called the standing wave ratio. The standing wave ratio is a measure of the degree of mismatch between the load and the line.

IMPORTANT DEFINITIONS

BALANCED NETWORK—A network which has the same impedance in both sides or lines.

BALUN—A device used to transfer energy from a balanced line to an unbalanced line.

CHARACTERISTIC IMPEDANCE—The input impedance of an infinitely long transmission line.

COAXIAL CABLE—A type of transmission line in which a central conductor is mounted coaxially within a surrounding metallic covering.

IMPEDANCE MATCHING—The process of matching one impedance to another.

IMPEDANCE TRANSFORMING—The process of transforming a given impedance to a different value.

ISOLATION PAD—A resistance network used to reduce the variations in input impedance caused by variations in an external load impedance.

MISMATCH—The condition existing when the load impedance does not have the desired value.

NONRESONANT LINE—A transmission line terminated in its characteristic impedance. All of the transmitted energy is absorbed by the load and none is reflected back to the source. There are no standing waves on a nonresonant line.

RESONANT LINE—A transmission line terminated in a load which is not equal to its characteristic impedance. Some of the transmitted energy is reflected from the load back toward the source, thereby producing standing waves.

STANDING WAVE RATIO (SWR)—The ratio between the maximum and minimum values of the standing waves of voltage or current along a transmission line. The standing wave ratio is a measure of the degree of mismatch between the load and the characteristic impedance of the line.

STANDING WAVES—Stationary variations in voltage or current along a resonant transmission line.

UNBALANCED NETWORK—A network in which there are different impedances in each side or line.

ESSENTIAL SYMBOLS AND EQUATIONS

E_{MAX}—maximum voltage

E_{MIN}—minimum voltage

I_{MAX}—maximum current

I_{MIN}—minimum current

N—number of receivers

N_P—number of primary turns

N_S—number of secondary turns

R_{IN}—input resistance

R_L—load resistance

R_{OUT}—output resistance

R_S—source resistance

R_1, R_2, R_3—resistors

SWR—standing wave ratio

Z_{IN}—input impedance

Z_O—characteristic impedance

Z_{OUT}—output impedance

Z_P—primary impedance

Z_S—secondary impedance

$$Z_P = \left(\frac{N_P}{N_S}\right)^2 Z_S \qquad (1)$$

$$R_{IN} = R_1 + \frac{R_2 R_L}{R_2 + R_L} \qquad (2)$$

$$R_{OUT} = \frac{R_2\,(R_1 + R_S)}{R_2 + (R_1 + R_S)} \qquad (3)$$

$$R_{IN} = \frac{R_2\,(R_1 + R_L)}{R_2 + (R_1 + R_L)} \qquad (4)$$

ESSENTIAL SYMBOLS AND EQUATIONS
(Continued)

$$R_{OUT} = R_1 + \frac{R_2 R_S}{R_2 + R_S} \tag{5}$$

$$R_{IN} = R_1 + \frac{R_2\,(R_3 + R_L)}{R_2 + (R_3 + R_L)} \tag{6}$$

$$R_2 = \frac{R_1\,(N - 1)}{2} \tag{7}$$

$$SWR = \frac{E_{MAX}}{E_{MIN}} = \frac{I_{MAX}}{I_{MIN}} \tag{8}$$

$$SWR = \frac{Z_O}{R_L}, \text{ or } \frac{R_L}{Z_O} \tag{9}$$

$$Z_{IN} = \frac{{Z_O}^2}{Z_{OUT}} \tag{10}$$

$$Z_O = \sqrt{Z_{IN} \times Z_{OUT}} \tag{10a}$$

PRACTICE EXERCISE SOLUTIONS

1. (a) source.—An amplifier input circuit is the load.

2. (c) A load resistance greater than the source resistance.—The generator voltage divides between the source and load resistances in proportion to their respective resistances. Thus, the greatest voltage is developed across the largest resistance.

3. (b) A dynamic microphone.—A ceramic microphone has a high impedance, around 250,000 ohms. It can be connected directly to the input of a voltage amplifier. A dynamic microphone, however, has a very low impedance, often about 20 ohms.

4. (a) high impedances.—The impedance of a ceramic phone pickup may be around 500,000 ohms, whereas the impedance of an electromagnetic pickup may be as low as 25 ohms.

5. (a) poor impedance match.—Typical output impedances of a grounded emitter transistor amplifier range from 30,000 ohms to 50,000 ohms, whereas typical input impedances of a grounded base transistor amplifier range from 30 ohms to 150 ohms.

6. The grounded collector configuration.—The input and output impedances of the grounded collector configuration can be made to match the input and output impedances of both the grounded emitter and grounded base configuration.

7. (a) equal to the source impedance.—However, maximum power transfer is not always the most important consideration in transferring electric energy from a source to a load. Other considerations include gain, efficiency, frequency response and distortion.

8. A transformer.

9. 25: (step-down).—Using Equation 1:

$$Z_P = \left(\frac{N_P}{N_S}\right)^2 Z_S$$

$$\frac{N_P}{N_S} = \sqrt{\frac{Z_P}{Z_S}} = \sqrt{\frac{2500}{4}} = \sqrt{625} = 25.$$

10. (1) The two 8-ohm speakers can be connected in parallel between the 4-ohm tap and ground, or (2) the two 8-ohm speakers can be connected in series between the 16-ohm tap and ground.

PRACTICE EXERCISE SOLUTIONS (Continued)

11. (b) load.—The load is connected across the shunt arm when the load impedance is greater than the source impedance.

12. (a) 100 ohms.—Using Equation 2,

$$R_{IN} = R_1 + \frac{R_2 R_L}{R_2 + R_L}$$

$$= 80 + \frac{45 \times 36}{45 + 36} = 80 + 20 = 100 \text{ ohms.}$$

13. True

14. (b) an H pad.—An H pad has equal series impedances in both sides or lines, whereas in a T pad all the series impedance is in one side.

15. The capacitance neutralizes the inductive component of the load.

16. (b) less than the impedance between the two end terminals.—The inductance or capacitance of a parallel resonant circuit is frequently tapped to obtain an input or output resistance less than that of the entire circuit. Another advantage of a circuit like that of Figure 15 is that a low source or load resistance can be connected between the tap and the lower terminal without appreciably lowering the Q of the circuit as it would do if it were connected between the two end terminals.

17. (a) increase.—Since the impedance of a parallel resonant circuit is maximum at resonance, the apparent load resistance (the impedance presented to the source) increases.

18. Because a portion of L is neutralized by the capacitance provided by C_2.

19. Coaxial transmission line is made up of a wire mounted inside of, and coaxially with, a metallic outer conductor. The inner conductor is supported by a dielectric material or by insulating spacers at regular intervals.

20. The characteristic impedance increases.—Moving the wires farther apart decreases the capacitance per unit length of the line which, in turn, increases the shunt impedance of the line.

21. No effect.—The characteristic impedance of a transmission line is the impedance of an infinitely long line and is determined by its series and shunt resistances and reactances per unit length.

22. The current and voltage are in phase.—In a nonresonant line, all of the energy is absorbed by the load, and the line is resistive.

PRACTICE EXERCISE SOLUTIONS (Continued)

23. Terminating the line in a load equal to the characteristic impedance of the line.

24. (a) resonant transmission lines.—A nonresonant line is terminated in its characteristic impedance. All of the energy is absorbed by the load and none is reflected back to produce standing waves.

25. 3.

26. (a) increases.—SWR is a measure of the degree of mismatch between a transmission line and its load.

27. 1.—When the load impedance equals the characteristic impedance of the transmission line, no energy is reflected from the load back to the source. Thus, all values of voltage on the line are equal (that is, there are no maximums and minimums), so that the ratio $E_{MAX}/E_{MIN} = 1$.

28. (b) parallel resonant circuit.—The ratio between the voltage and current standing waves is now maximum at the source.

29. 3333 ohms (approx.).—Using Equation 10:

$$Z_{IN} = \frac{Z_O^2}{Z_{OUT}} = \frac{(500)^2}{75} = 3333 \text{ ohms (approx.).}$$

30. 190 ohms (approx.).—Using Equation 10a:

$$Z_O = \sqrt{Z_{IN} \times Z_{OUT}} = \sqrt{500 \times 72}$$

$$= 190 \text{ ohms (approx.).}$$

DE VRY INSTITUTE OF TECHNOLOGY
4141 BELMONT AVENUE, CHICAGO, ILLINOIS 60641

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7440A
EXAMINATION CHECK SHEET

1. C - TO OBTAIN THE DESIRED IMPEDANCE MATCH, SPEAKERS ARE OFTEN CONNECTED TO AN AMPLIFIER BY MEANS OF -- TRANSFORMERS.
The turns ratio of the transformer is selected to provide the desired impedance match.

2. C - WHICH OF THE FOLLOWING TRANSISTOR CIRCUITS PROVIDES A HIGH INPUT IMPEDANCE AND A LOW OUTPUT IMPEDANCE? -- GROUNDED COLLECTOR.
The emitter follower or grounded collector amplifier provides a high input impedance and a low output impedance.

3. B - MAXIMUM POWER IS TRANSFERRED FROM A SOURCE TO A LOAD WHEN THE LOAD IMPEDANCE IS EQUAL TO -- THE SOURCE IMPEDANCE.
Although maximum power transfer is obtained under these conditions, a perfect match may be disregarded in favor of a match that provides low distortion or improved frequency response.

4. C - WHAT IS THE TURNS RATIO OF A TRANSFORMER REQUIRED TO MATCH A 4-OHM SPEAKER TO AN AMPLIFIER WITH A REQUIRED LOAD IMPEDANCE OF 8000 OHMS? -- 44.7: 1.
The turns ratio is equal to the square root of the impedance ratio.

$$N = \sqrt{\frac{Z_P}{Z_S}} = \sqrt{\frac{8000}{4}} = \sqrt{2000} = 44.7$$

5. C - AN AUDIO OUTPUT TRANSFORMER HAS 4-, 8-AND 16-OHM TAPS. WHICH OF THE FOLLOWING MULTIPLE SPEAKER ARRANGEMENTS IS CORRECT? -- FOUR 16-OHM SPEAKERS PARALLEL CONNECTED TO THE 4-OHM TAP.
Four 16-ohm speakers in parallel have an equivalent resistance of 4 ohms.

6. B - WHICH OF THE FOLLOWING TYPES OF ISOLATION PADS WOULD MOST LIKELY BE USED TO ISOLATE ONE BALANCED CIRCUIT FROM ANOTHER? -- AN H NETWORK.
The T, L and π networks are used with unbalanced circuits.

7. D - WHAT IS THE CHARACTERISTIC IMPEDANCE OF A ONE-QUARTER WAVELENGTH TRANSMISSION LINE USED TO MATCH A 200-OHM SOURCE TO AN 800-OHM LOAD? -- 400 OHMS.
The line impedance is equal to

$$Z_O = \sqrt{Z_{IN} \times Z_{OUT}} = \sqrt{200 \times 800} = \sqrt{160{,}000} = 400 \text{ ohms}$$

8. A - WHAT IS THE STANDING WAVE RATIO IF A TRANSMISSION LINE WITH A CHARACTERISTIC IMPEDANCE OF 50 OHMS IS CONNECTED TO A LOAD IMPEDANCE OF 75 OHMS? -- 1.5: 1.
The SWR is equal to SWR =

$$\frac{Z_L}{Z_O} = \frac{75}{50} = 1.5$$

9. D - WHEN A ONE-QUARTER WAVELENGTH TRANSMISSION LINE IS TERMINATED IN A SHORT, THE IMPEDANCE AT THE INPUT END -- IS MAXIMUM.
A quarter wavelength transmission line acts like an impedance transformer.

10. D - TO THE SOURCE, A SHORTED LINE SECTION ONE-QUARTER WAVELENGTH LONG IS EQUIVALENT TO -- A PARALLEL RESONANT CIRCUIT.
A shorted half wavelength line is equivalent to a series resonant circuit.

QUESTIONS

IMPORTANT—These instructions **MUST** be accurately followed to avoid loss, or errors in grading.

Indicate your answer on this sheet by filling in the box for the most correct answer to each question, as illustrated in the example below.

When all questions have been answered, place the answer card in the proper position to line up the boxes on the card with the boxes on the sheet.

Next, copy the complete lesson code into the space provided on the card, and fill in the answer boxes to correspond with those previously filled in on this sheet.

Before mailing, be certain your correct student number, name and address appear on the card.

LESSON CODE
7440A

Example:

A ☐ B ■ C ☐ D ☐ A common dairy product is
(A) parsley. (B) milk. (C) honey. (D) endive.

1. A ☐ B ☐ C ☒ D ☐ **To obtain the desired impedance match, speakers are often connected to an amplifier by means of**
(A) transmission lines. (B) resonant circuits. (C) transformers. (D) resistor networks.

2. A ☐ B ☐ C ☒ D ☐ **Which of the following transistor circuits provides a high input impedance and a low output impedance?**
(A) Grounded emitter. (B) Grounded base. (C) Grounded collector. (D) Grounded cathode.

3. A ☐ B ☒ C ☐ D ☐ **Maximum power is transferred from a source to a load when the load impedance is equal to**
(A) one-half the source impedance. (B) the source impedance. (C) twice the source impedance. (D) three times the source impedance.

4. A ☐ B ☐ C ☒ D ☐ **What is the turns ratio of a transformer required to match a 4-ohm speaker to an amplifier with a required load impedance of 8000 ohms?**
(A) 22.5:1. (B) 20:1. (C) 44.7:1. (D) 33.3:1.

5. A ☐ B ☐ C ☒ D ☐ **An audio output transformer has 4-, 8- and 16-ohm taps. Which of the following multiple speaker arrangements is correct?**
(A) Four 16-ohm speakers parallel connected to the 8-ohm tap. (B) Two 8-ohm speakers series connected to the 4-ohm tap. (C) Four 16-ohm speakers parallel connected to the 4-ohm tap. (D) Two 16-ohm speakers series connected to the 8-ohm tap.

6. A ☐ B ☒ C ☐ D ☐ **Which of the following types of isolation pads would most likely be used to isolate one balanced circuit from another?**
(A) A T network. (B) An H network. (C) An L network. (D) A π network.

7. A ☐ B ☐ C ☐ D ☒ **What is the characteristic impedance of a one-quarter wavelength transmission line used to match a 200-ohm source to an 800-ohm load?**
(A) 300 ohms. (B) 350 ohms. (C) 450 ohms. (D) 400 ohms.

8. A ☒ B ☐ C ☐ D ☐ **What is the standing wave ratio if a transmission line with a characteristic impedance of 50 ohms is connected to a load impedance of 75 ohms?**
(A) 1.5:1. (B) 1:1. (C) 3:1. (D) 2.5:1.

9. A ☐ B ☐ C ☐ D ☒ **When a one-quarter wavelength transmission line is terminated in a short, the impedance at the input end**
(A) varies with signal strength. (B) is equal to the characteristic impedance. (C) is minimum. (D) is maximum.

10. A ☐ B ☐ C ☐ D ☒ **To the source, a shorted line section one-quarter wavelength long is equivalent to**
(A) an inductive reactance. (B) a capactive reactance. (C) a series resonant circuit. (D) a parallel resonant circuit.

QUESTIONS

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A ☐
B ■
C ☐
D ☐

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(A) parsley. (B) milk. (C) honey. (D) endive.

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To the source, a shorted line section one-quarter wavelength long is equivalent to
(A) an inductive reactance. (B) a capactive reactance. (C) a series resonant circuit. (D) a parallel resonant circuit.

MODULATION AND DEMODULATION

7445

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A technician adjusts some electronic equipment in a synchronous communications (SYNCOM) satellite, which will serve as an orbiting relay station. FM transmitters and receivers in the satellite will relay communications between continents.

Courtesy Aerospace Group Hughes Aircraft Co.

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Laziness grows on people; it begins in cobwebs and ends in iron chains. The more business a man has to do the more he is able to accomplish, for he learns to economize his time.

—Sir M. Hale

MODULATION AND DEMODULATION

This lesson is divided into two parts. The first part of the lesson covers the principles of modulation, while the second part covers the principles of demodulation and detection. You must therefore study the information presented in this first portion (Part 1) of the lesson and the succeeding portion (Part 2) before you complete the overall lesson examination which is at the end of Part 2. Study the lesson material carefully and be sure to answer all of the Practice Exercise questions as you proceed. By doing this, you will greatly increase your understanding of all the material presented.

PART 1—MODULATION

As the term is commonly used, **MODULATION** is the process of adding information to a **CARRIER.** This carrier is most often radio-frequency energy. Radio-frequency energy may be transmitted from one place to another without wires. Thus, a radio-frequency carrier which is modulated can carry information from place to place without wires.

There are two basic methods of adding information to a carrier. They are called **AMPLITUDE MODULATION** and **FREQUENCY MODULATION.** With amplitude modulation (AM), the information is added by changing the amplitude or level of the carrier. With frequency modulation (FM), the frequency of the carrier is changed.

The commercial AM and FM radio broadcast stations which are located in almost every major city serve as typical examples of the use of amplitude and frequency modulation. The AM stations, which operate between 535 and 1605 kHz, are capable of transmitting information such as news, sports events and music over a considerable distance.

FM radio stations, which operate between 88 and 108 MHz, provide the same services as the AM stations. However, the use of frequency modulation provides a distinct advantage. Electrical interference, both manmade and natural, does not produce as much distortion in FM signals as it does in AM signals. This interference, called static or noise, usually affects the amplitude rather than the frequency of a transmitted signal. Communication systems which use AM may, therefore, occasionally be affected by noise which would not affect FM systems.

In this lesson you will study the basic principles behind amplitude and frequency modulation. You will also examine many of the basic circuits which are used to produce AM and FM signals. Study this lesson carefully because it contains information which is vital to you. The modulation systems described in this lesson form the basis of all modern communication systems.

THEORY OF AMPLITUDE MODULATION

To help understand amplitude modulation, let Figure 1-1A represent a high-frequency carrier wave. Now, assume that Figure 1-1B is the low-frequency information signal that we want to transmit. This information signal is usually called the **MODULATING SIGNAL**. In standard broadcast systems, the modulating signal is usually an audio-frequency (a-f) signal such as the output of a microphone.

The object is to combine the modulating signal of Figure 1-1B with the carrier of Figure 1-1A in such a way that THE INSTANTANEOUS CARRIER AMPLITUDE WILL BE CONTROLLED BY THE MODULATING SIGNAL AMPLITUDE. This is amplitude modulation.

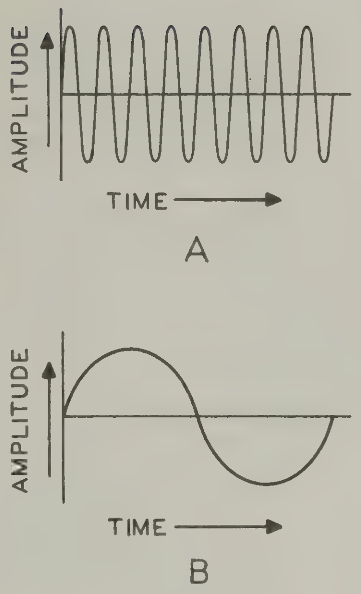


Figure 1-1

Let's see what happens if the carrier and modulating signal are applied to a resistor network. Figure 1-2A shows such a network. The output would look like Figure 1-2B. The carrier is NOT amplitude modulated in this figure. The two waves of Figure 1-1 have simply been added together. Notice that the waveshape of Figure 1-2B still has the same amplitude at all places. It is simply moved up and down.

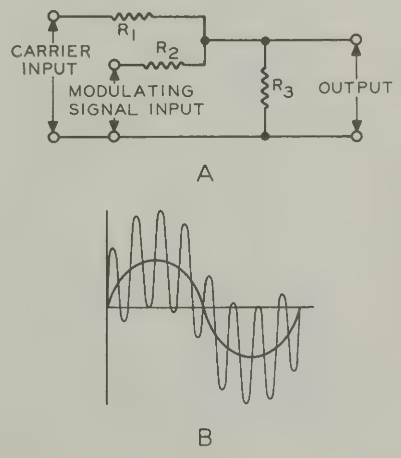


Figure 1-2

To obtain a change in amplitude of the carrier, another element must be added to the circuit. Figure 1-3 shows a circuit similar to that of Figure 1-2, but with a diode added. A diode is a NONLINEAR element. This means that the output is not always exactly proportional to the input. Such a nonlinear element is necessary to produce amplitude modulation.

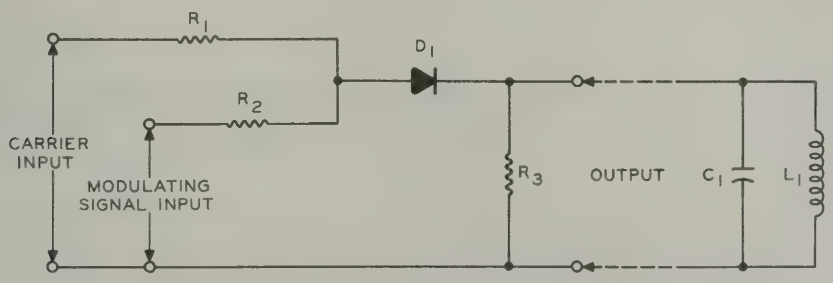


Figure 1-3

The voltage applied to diode D_1 in Figure 1-3 is a combination of carrier and modulating signal such as shown in Figure 1-2B. Remember, however, that a diode conducts current in one direction much better than the other. Therefore, current is through D_1 and R_3 of Figure 1-3 only when the anode of D_1 is more positive than the cathode.

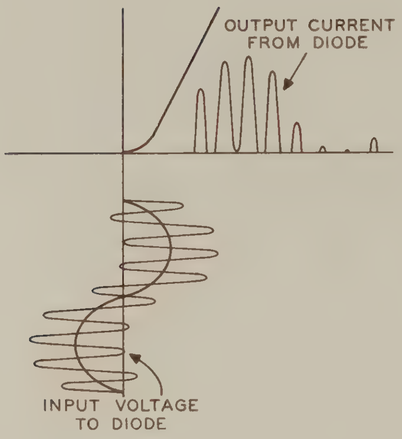


Figure 1-4

Figure 1-4 shows the current which results from applying the combination of carrier and modulating signal to D_1. Because there is no current when the applied voltage is negative, the current does not have the same waveshape as the applied voltage. The amplitude of the current waveshape follows the modulating signal waveshape. Because this current is through R_3, the output voltage developed has a shape similar to that of the current wave. The circuit of Figure 1-3 can, therefore, be used to produce an amplitude-modulated output voltage.

An actual modulation circuit usually includes an LC circuit, here represented by L_1 and C_1, that is resonant to the carrier frequency. When L_1 and C_1 are resonant to the carrier frequency, they modify the shape of the output voltage wave. The ringing or oscillating action of this resonant LC combination provides a negative half for each cycle, which is an upside down copy of the positive half. If the LC components are properly chosen, each negative half-cycle will have approximately the same amplitude as that particular positive half-cycle. The result is an output voltage with the waveshape of Figure 1-5. THIS IS THE WAVESHAPE NORMALLY ASSOCIATED WITH AMPLITUDE MODULATION. Notice that the amplitude of the carrier follows the shape of the modulating signal.

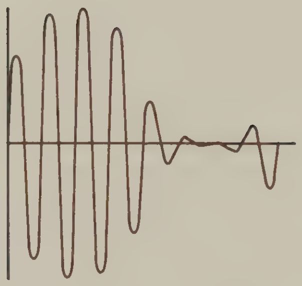


Figure 1-5

The original carrier, the modulating signal, and the result of combining them through amplitude modulation are all shown in Figure 1-6. From this figure, you can see how the amplitude of the modulated carrier of Figure 1-6C corresponds to the shape of the modulating signal of Figure 1-6B. Notice the dashed lines which follow the peaks of the modulated carrier of Figure 1-6B. The pattern formed by these dashed lines is called the **MODULATION ENVELOPE**. It is the pattern that would be seen on an indicating device such as an oscilloscope.

Amplitude modulation can be obtained with a variety of circuits, provided that at least one nonlinear element is included in each. Diodes, transistors and vacuum tubes all find wide use as nonlinear elements in such circuits.

AM SIDEBANDS

The modulator circuit of Figure 1-3 includes a resonant LC circuit. This circuit is added to provide the lower half of the Figure 1-5 waveshape. The negative alternations result from the ringing action of L_1 and C_1. Although this oscillating action should be sufficient to provide these alternations, the circuit must not oscillate too freely. Another way to say this is that the Q of the circuit must not be too high. This is true of any LC circuit which handles a modulated carrier. A circuit with a very high Q would oscillate indefinitely, and the envelope of Figure 1-5 would be lost. The envelope of Figure 1-6A would result.

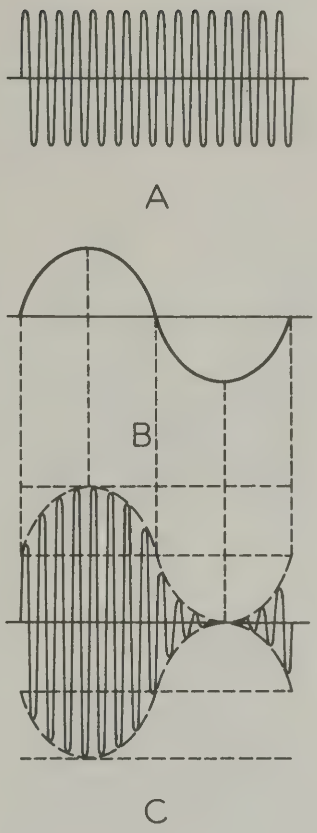


Figure 1-6

The modulated waveshape of Figure 1-5 can be described by a lengthy mathematical expression. While the expression is not of interest to us now, it does allow an interesting comparison to be made. It shows that the waveshape of Figure 1-5 could be produced by adding three high-frequency signals. They would be (1) the carrier, (2) a high-frequency signal equal to the sum of the carrier and modulating signal frequencies, and (3) a high-frequency signal equal to the difference between the carrier frequency and the modulating frequency. Thus, when two signals of different frequencies are mixed in a nonlinear circuit such as the one shown in Figure 1-3, the output contains the sum and difference frequencies and one or both of the original frequencies. For example, consider a 1000-kHz carrier amplitude modulated by a 1000-Hz audio modulating signal. This could be analyzed as a combination of 1000 kHz, 1001 kHz (1000 kHz + 1000 Hz), and 999 kHz (1000 kHz − 1000 Hz) signals.

The sum and difference signals are called **SIDEBAND SIGNALS** of the modulated carrier and are located in the **SIDEBANDS**. The lower, or difference, frequency (999 kHz) is called the lower sideband frequency. The higher, or sum, frequency (1001 kHz) is called the upper sideband frequency. Figure 1-7 is a graph showing the carrier and sideband frequencies. The carrier is at the 1000-kHz point, and the sideband signals are at points 1 kHz above and below the carrier frequency.

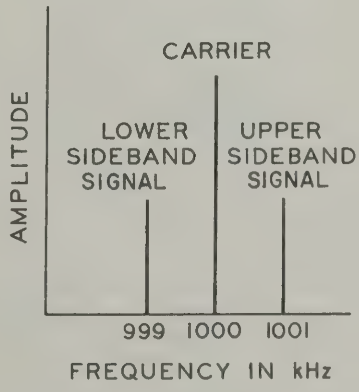


Figure 1-7

By using the concept of sidebands, we can make our work with modulated carriers easier. For one thing, LC circuits are often used with modulated signals. These circuits can be analyzed most easily in terms of Q and bandpass. For example, an LC circuit which passes a modulated carrier must be able to pass the sideband frequencies as well as the carrier. We can see the logic of this by reviewing the ringing action described earlier. Thus, we have a convenient tool in the sideband explanation which gives us a better understanding of the modulation principle.

When a carrier frequency is amplitude modulated by an audio signal, an output containing four frequencies is obtained. These are: the carrier, the upper sideband frequency, the lower sideband frequency and the modulating audio frequency. However, the modulating signal often is not desired as an output. When the resonant LC circuit of Figure 1-3 is connected across R_3, the output contains very little of the modulating frequency. This is because the circuit is tuned to pass the carrier and sidebands, while greatly reducing the amount of the audio signal in the output.

Now, let's look again at Figure 1-7, which shows a carrier and the sidebands that result from amplitude modulation. Notice that the left axis of Figure 1-7 is labeled AMPLITUDE. The amplitude of the sideband signals depends on the amplitude of the modulating signal compared to that of the carrier. With no modulating signal, there will be no sideband signals. A small modulating signal will produce low-amplitude sideband signals. A larger modulating signal will increase the amplitude of the sideband signals.

AM MODULATION PERCENTAGE

The amount of modulation that takes place in AM transmission systems is expressed in percentage. For example, with 100% modulation the modulating signal causes the carrier envelope to vary from zero to twice its unmodulated value. This is the maximum **MODULATION PERCENTAGE** which can normally be used.

Figure 1-8A shows an unmodulated carrier. Figure 1-8B shows the same carrier amplitude modulated 100%. Notice that the envelope decreases to zero and increases to twice the unmodulated level (the total amplitude from the lower peak to the upper peak is twice the amplitude of the unmodulated wave of Figure 1-8A).

In Figure 1-8C, 50% modulation is shown where the envelope decreases to 50% or half of the unmodulated level (the amplitude X is half the amplitude of the unmodulated wave of Figure 1-8A). It also increases 50% above the unmodulated level (the amplitude Y is one and a half times the amplitude of the unmodulated wave of Figure 1-8A).

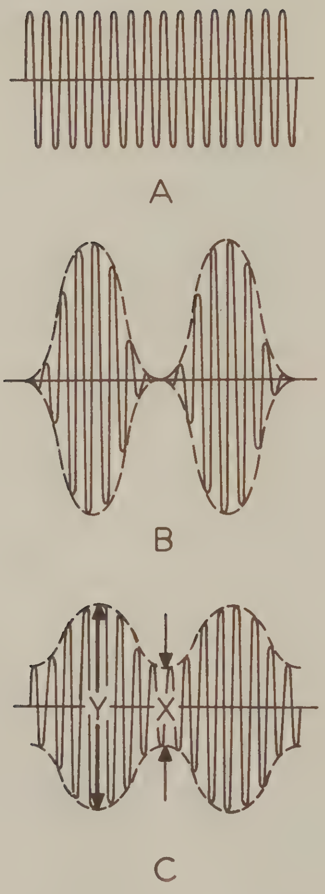


Figure 1-8

It is sometimes desirable to determine the percentage of modulation from envelope patterns such as those of Figure 1-8. Such a pattern, for example, might be viewed with an oscilloscope. In this case, determine dimensions X and Y as shown in Figure 1-8C. They can be measured in centimeters, fractions of an inch or any convenient unit. Figure 1-8C is divided into convenient but arbitrary units. Dimension X is 2 units and dimension Y is 6 units. To find the percentage of modulation from a pattern such as shown in Figure 1-8C, use the following expression:

$$\%\ \text{MODULATION} = \frac{Y - X}{Y + X} \times 100. \qquad (1)$$

Use the units of Figure 1-8C in this expression as an example:

$$\%\ \text{MODULATION} = \frac{Y - X}{Y + X} \times 100 = \frac{6 - 2}{6 + 2} \times 100 = \frac{4}{8} \times 100 = 50\%.$$

This method is most accurate when the modulating signal has a sinusoidal shape.

The maximum percentage of modulation generally used is 100%. With 100% amplitude modulation, as shown in Figure 1-8B, the envelope just closes at one point of each cycle. That is, the top and bottom lines of the envelope meet, but their shape is not distorted.

Now, consider what happens with more than 100% modulation. Figure 1-9 shows the result of such a condition. This is called **OVERMODULATION.** Compare this with Figure 1-8C. Notice how the envelope shape is flattened or distorted in Figure 1-9. The envelope should be a faithful copy of the modulating signal. Overmodulation distorts the modulation envelope and therefore distorts the information being carried. If a broadcast transmitter were overmodulated, you would hear distorted sound when that station was tuned in on a receiver.

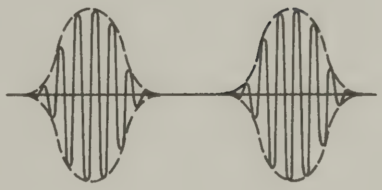


Figure 1-9

Besides distorting sound for the listener, overmodulation at a station creates other undesirable effects. When the envelope of a transmitted carrier is distorted as in Figure 1-9, it can cause interference with the carriers and sidebands from other stations. Therefore, overmodulation is not permitted in most types of radio wave transmission.

On the other hand, it is desirable to modulate a carrier as near 100% as possible without causing overmodulation. Since the carrier merely serves as a reference in transmitting the modulating signal through space to the receiver, a large amplitude carrier with a very small percentage of modulation would be a waste of energy.

For normal voice or music transmission, the modulation signal may not have a simple sinusoidal shape. Music, for example, is made up of a number of sinusoidal signals occurring at the same time. Thus, a carrier which is amplitude modulated by music or speech could have the appearance of Figure 1-10A. This figure illustrates amplitude modulation that reaches nearly 100%.

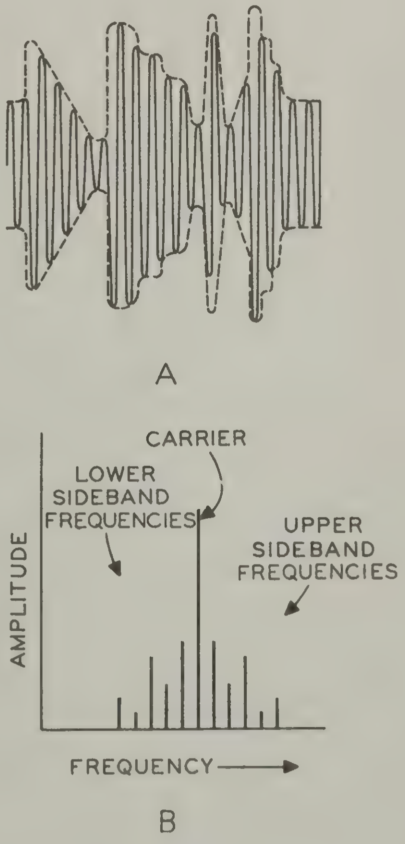


Figure 1-10

When the modulating signal includes more than one frequency, the sidebands also include more frequencies. For example, the waveshape of Figure 1-10A might produce sideband signals as shown in Figure 1-10B. Both the upper sideband and the lower sideband include a number of frequencies. Notice, however, that they are in pairs. That is, a frequency included in the lower sideband will always have a counterpart in the upper sideband. If the lower sideband contains signals with frequencies of 995, 998 and 999 kHz, the upper sideband will contain signals with frequencies of 1001, 1002 and 1005 kHz.

This AM modulation monitor measures the percent of modulation.
Courtesy Gates Radio Co.

Whenever a carrier is amplitude modulated by a modulating signal, two sidebands are produced—the upper sideband and the lower sideband. The number of signals in each sideband is determined by the nature of the modulating signal. For example, when a 1-kHz signal and a 5-kHz signal are used to simultaneously modulate a carrier, two pairs of sideband signals are generated. One pair of sideband signals is separated from the carrier by 1 kHz and the other pair of sideband signals is separated from the carrier by 5 kHz. All of the signals above the carrier comprise the upper sideband while all of the signals below the carrier comprise the lower sideband.

Occasionally, terminology that is not exactly correct may be used when describing a carrier and its sidebands. Figure 1-10B, for example, sometimes might be described as "the carrier with its five upper sidebands and five lower sidebands." To be technically correct, it should be described as "the carrier with five signals in its upper sideband and five signals in its lower sideband."

POWER

In an amplitude modulation system, the average power at the carrier frequency remains constant as long as overmodulation does not occur. This is true whether it is being modulated or not. However, the power in each sideband is proportional to the strength of the modulating signal. Therefore, the total power transmitted varies as the amplitude of the modulating signal changes.

With normal modulation (between 0 and 100%), equal power is contained in each sideband. When the percentage of modulation is zero, the sideband power is zero. At 100% modulation, each sideband of the pair contains $^1/_4$ as much power as the carrier. Both sidebands combined contain $^1/_2$ as much power as the carrier. Therefore, increasing the modulation from 0% to 100% increases the transmitted power to $1^1/_2$ times the carrier power alone. For example, suppose that an AM broadcast station with an unmodulated carrier power of 1000 watts is modulated 100% by a sinewave signal. The TOTAL SIDEBAND POWER is 500 watts (half the carrier power) and the TOTAL RADIATED POWER is 1000 + 500 = 1500 watts.

Total sideband power for any pair of sidebands can be found by using the following formula:

$$P_{SB} = \frac{M^2}{2} P_C \qquad (2)$$

where:

P_{SB} = total sideband power in watts

M = % of modulation divided by 100

P_C = carrier power in watts.

Let's try an example. Consider an AM broadcast transmitter with a carrier power of 1000 watts and 90% modulation. The total sideband power is:

$$\begin{aligned} P_{SB} &= \frac{.9^2}{2} \times 1000 \\ &= \frac{.81}{2} \times 1000 \\ &= 405 \quad \text{watts.} \end{aligned}$$

The power in one sideband is half the power of both sidebands. Therefore, when the power in a pair of sidebands is 405 watts, the power in each sideband is 405 ÷ 2 = 202.5 watts.

Often, the modulated carrier is intended to be transmitted through the air. This is the case with the modulated carrier developed by a broadcast radio station. Here, the modulated carrier is fed into an antenna system from which it is then radiated.

The authorized power fed to the antenna system is determined by an agency of the federal government, such as the FCC (Federal Communications Commission) in the United States or the DOT (Department of Transport) in Canada. Power ratings generally refer to an unmodulated carrier. Therefore, a 500-watt transmitter ~~for an AM broadcast~~ station produces 500 watts of carrier power.

Actual power fed to the antenna of a broadcast transmitter must be measured constantly. This is done by either the direct or indirect method. The direct method is based on antenna current and resistance measurements. Antenna current is continuously monitored by meters in the antenna feed lines. Antenna resistance is measured at the common signal input to the antenna.

In the indirect method of determining output power, the input power of the final transmitter stage is found and multiplied by an efficiency factor. Input power of a tube-type transmitter is equal to the product of average plate current and dc plate voltage of the final transmitter stage which feeds the antenna. Efficiency factors are determined by the FCC or the DOT.

HIGH- AND LOW-LEVEL MODULATION

Modulation methods are divided into two groups, **HIGH-LEVEL MODULATION** and **LOW-LEVEL MODULATION**. High-level modulation is modulation which occurs in the PLATE OR COLLECTOR CIRCUIT of the final r-f stage that feeds the antenna. Low-level modulation is modulation of the carrier at a point preceding the final r-f stage. The final r-f stage is also called the final power amplifier stage.

The stage in which modulation takes place is often called the **MODULATED STAGE** or the **MODULATED AMPLIFIER**. The stage that supplies the modulating signal is normally called the **MODULATOR**.

In high-level modulation, the r-f stages preceding the final or modulated stage are not necessarily operated as linear amplifiers. These stages may be operated Class C, resulting in high efficiency (about 65% to 85%). However, high-level modulation has the disadvantage of requiring more power for modulation. Therefore, the section used for high-level modulation usually has more stages than one used for low-level modulation.

For 100% high-level modulation, the modulator stage must be capable of varying the carrier level from zero to twice the amplitude of the unmodulated carrier. To do this, the modulator stage must supply all of the sideband power. When the carrier power is 1000 watts, the modulator stage must supply 500 watts of power for 100% modulation; when the carrier is 50,000 watts, the modulator stage must supply 25,000 watts for 100% modulation.

Low-level modulation requires lower modulating power because modulation occurs at a lower r-f power level. With low-level modulation, all stages following the modulated stage are usually operated linear class A, AB or B so that the envelope of the modulated carrier will not be distorted. A disadvantage of this system is the reduction of the efficiency in the r-f stages following the modulated stage to 50% or 60%. However, the power requirement of the modulator is also reduced.

MODULATION CIRCUITS

There are several ways to amplitude modulate an r-f carrier. In systems which use vacuum tubes, the modulating signal can be applied to the plate or control grid of the tube in the modulated stage. If a pentode is used, the modulating signal can be applied to the screen grid, suppressor grid, control grid, or plate. Each system has characteristics which may make it a desirable method of modulation for a given application.

Plate Modulation

PLATE MODULATION is commonly used in modulation systems which employ vacuum tubes. This is high-level modulation when it occurs in the final r-f stage. Plate modulation produces amplitude modulation by adding the modulating signal to the plate voltage normally applied to the plate circuit of a vacuum tube. This signal adds to the plate input power and, therefore, adds to the total power output of the modulated stage.

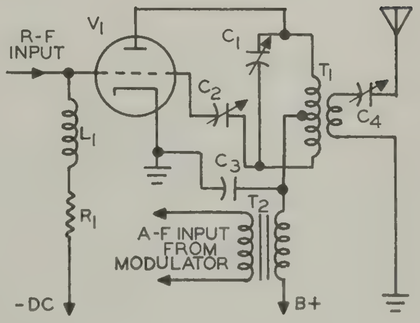


Figure 1-11

To see how a high-level plate modulation system operates, let's look at Figure 1-11. Triode V_1 is the r-f modulated amplifier. The grid of V_1 is biased at the proper operating point (usually class C) by the bias supply labeled −DC. The unmodulated r-f carrier from an r-f amplifier is applied to the grid of V_1.

The plate supply voltage, B+, is connected through the secondary winding of T_2 and the resonant tank, C_1 and T_1, to the plate of V_1. V_1 is neutralized by feeding back part of the signal from the primary of T_1 through neutralizing capacitor C_2 to the grid of V_1. Capacitor C_3 is an r-f bypass capacitor which keeps r-f out of the modulator and power supply. The antenna circuit is tuned to resonance by means of C_4.

An audio-frequency signal from the modulator is applied to the primary of T_2 (the modulating transformer) for inductive coupling to the secondary of T_2. This a-f modulating signal is in series with B+. Depending on the polarity of the a-f signal, it alternately adds to or subtracts from the plate supply voltage, B+.

When the a-f signal developed across the secondary of T_2 is negative at the upper end of T_2, it is in opposition to plate supply voltage B+. This is the same as decreasing B+ by the value of the voltage across the secondary of T_2. For 100% modulation, the net plate voltage at this instant is zero. This condition exists only at the instant that the modulating voltage is at its maximum negative peak.

During the other alternation of the a-f voltage, the voltage developed across the T_2 secondary adds to B+, increasing the V_1 plate voltage. With 100% modulation, the voltage supplied to the C_1T_1 tank circuit is twice the value of the plate supply voltage, B+, at the instant the modulating signal reaches this peak.

In general, when a transmitter is modulated 100%, the total power radiated increases by 50% compared to the unmodulated carrier power. The additional power is in the sidebands and is supplied by the modulator. The output of modulation transformer T_2, at 100% modulation, is such that the plate voltage to the modulated stage varies between zero and twice the plate supply voltage, B+.

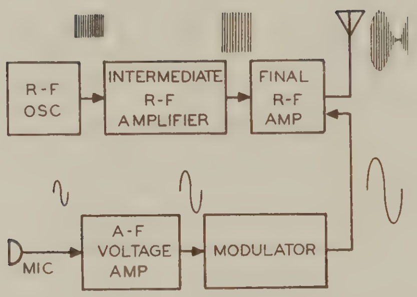


Figure 1-12

A block diagram of a simple AM transmitter using high-level plate modulation is shown in Figure 1-12. Five blocks represent the important signal stages of the transmitter. They are: the r-f oscillator, intermediate r-f amplifier, final r-f amplifier, the a-f voltage amplifier and the modulator. In this diagram, the low-frequency input is the output of a microphone.

This transmitter operates as follows: The r-f oscillator generates the carrier frequency. From the r-f oscillator, the carrier is applied to the intermediate r-f amplifier and then to the final r-f amplifier. The intermediate r-f amplifier can be operated in Class C for greatest efficiency since modulation occurs in the final r-f amplifier. This final r-f amplifier section of Figure 1-12 is also called the modulated stage. The intermediate amplifier section may be called the buffer amplifier, since it isolates the power amplifier from the oscillator.

The low-frequency sound signal is picked up by a microphone, changed to an electric signal and applied to an a-f voltage amplifier. Next, the amplified a-f signal is fed to the modulator, where it is further amplified. From here, the a-f signal goes to the modulated stage, where it is used to modulate the r-f carrier. This results in an amplitude-modulated output signal.

Screen Grid and Suppressor Grid Modulation

Normal plate modulation cannot be used to obtain 100% modulation with tetrode and pentode power amplifiers. This is because the plate current in a tetrode or pentode is relatively independent of the plate voltage; it depends more on the screen or suppressor grid voltage. For 100% modulation, the screen grid or suppressor grid voltage should be varied approximately the same percentage as the plate voltage.

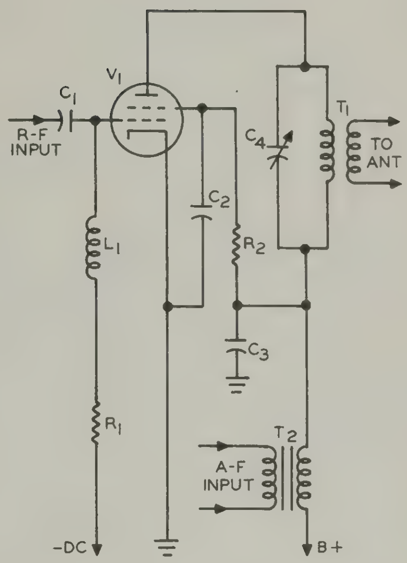


Figure 1-13

Figure 1-13 shows a form of **SCREEN GRID MODULATION**. The tube shown in this circuit is a tetrode, although a pentode could be used in a similar circuit. Tetrode V_1 and its components form the modulated stage. The unmodulated carrier is applied to the control grid of V_1 through coupling capacitor C_1. Resistor R_1 and r-f choke L_1 form the grid load. Capacitors C_2 and C_3 are r-f bypass capacitors. Variable capacitor C_4 and the primary of T_1 form the resonant output tank circuit. The antenna system is connected to the T_1 secondary.

Modulation is accomplished by varying the dc voltage on the screen grid and plate in step with the a-f modulating signal. The secondary of the modulation transformer, T_2, is connected in the plate and screen grid supply line. Audio-frequency voltages appearing across the secondary of T_2 alternately add to and subtract from the B+ voltage. These changes of voltage appear at the plate and screen grid of V_1. As a result, plate current and plate power vary in step with the modulating signal. To obtain a high percentage of modulation, the screen grid voltage is generally reduced from $^1/_3$ to $^1/_2$ of the voltage used if the tube were operated as an amplifier.

Although this modulation method is often referred to as simply screen grid modulation, it involves modulation at both the screen grid and plate. When only the screen grid is modulated, rather than both the screen grid and plate, the maximum modulation obtainable is about 80%. This particular type of modulation is often used in low-power fixed and mobile applications.

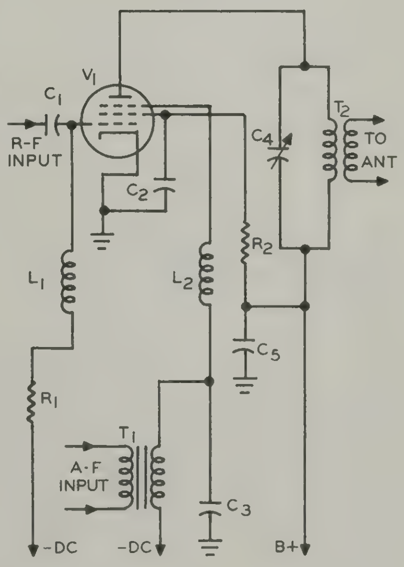


Figure 1-14

Figure 1-14 is the schematic of a modulated amplifier using **SUPPRESSOR GRID MODULATION**. The suppressor grid is connected in series with the secondary of the modulation transformer, T_1. A negative bias placed on the suppressor grid reduces the plate efficiency of the tube to about 35%. R_2 reduces the screen grid voltage to a value lower than the plate voltage. Capacitors C_2, C_3 and C_5 are r-f bypass capacitors. The output of the tube is applied to the antenna by way of a tuned plate circuit consisting of C_4 and the primary of T_2.

An a-f signal across the secondary of the modulation transformer increases or decreases the normal suppressor grid voltage. These changes in suppressor grid voltage cause changes in the amplifier output. The result is an amplitude-modulated r-f carrier with low distortion at a modulation of 90% to 95%. Without increasing the distortion to an objectionable level, 100% modulation is difficult to obtain. Suppressor grid modulation is often used in Class C amplifier stages.

Control Grid Modulation

Amplitude modulation can also be obtained by applying a modulating signal to the control grid of a modulated amplifier. This method of low-level modulation is called **CONTROL GRID MODULATION**. The main advantage of this type of modulation is that it requires only a low-power modulator. The efficiency of the modulated amplifier, however, is also low.

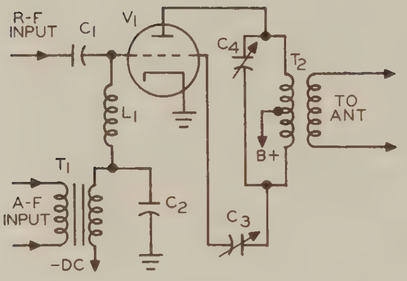


Figure 1-15

Figure 1-15 shows a final r-f amplifier stage using control grid modulation. The a-f modulating signal is applied to the grid of V_1 through modulation transformer T_1. An a-f signal, appearing across the secondary of T_1, alternately aids and opposes the grid bias. These changes of bias voltage cause the operating point of the Class C amplifier, V_1, to vary in step with the a-f modulating signal. The amount that the bias changes depends on the amplitude of the modulating signal. A large modulating signal produces greater changes of bias than a smaller modulating signal.

Since the grid bias controls the plate current, variations in grid bias produce similar variations in the plate current and plate circuit power. This varying energy is coupled from the tank circuit to the antenna by transformer T_2.

With control grid modulation, the low distortion obtained with plate modulation is also obtained, but at the expense of reduced output power and efficiency. However, this form of modulation has an advantage. Due to the amplification of a signal at the grid of V_1, a small modulating signal at the grid has as much effect as a much larger modulating signal applied to the plate circuit.

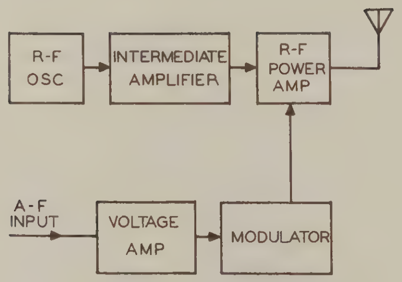


Figure 1-16 is a block diagram of a transmitter using control grid modulation. The r-f section (the upper portion of the figure) contains an r-f oscillator, an intermediate amplifier and an r-f power amplifier. The intermediate amplifier is also called a buffer. It isolates the oscillator from the modulated power amplifier. This assures a stable carrier frequency from the oscillator. Both the buffer and power amplifier can be operated Class C to provide a high percentage of efficiency.

Figure 1-16

The a-f section (the lower portion of the figure) consists of a low-frequency voltage amplifier and a modulator. The modulator used in this transmitter is a low-power amplifier instead of the high-power amplifier needed for plate modulation. The modulator output is applied to the grid of the r-f power amplifier. The resulting AM signal is fed from the power amplifier to the antenna. This signal is then transmitted to the receiver in the form of an electromagnetic wave.

The following Practice Exercise questions cover the subjects which you have just studied. They are:

THEORY OF AMPLITUDE MODULATION

AM SIDEBANDS

AM MODULATION PERCENTAGE

POWER

HIGH- AND LOW-LEVEL MODULATION

MODULATION CIRCUITS

PLATE MODULATION

SCREEN GRID AND SUPPRESSOR GRID MODULATION

1. What is the usual reason for modulating a carrier?

2. If two signals of different frequencies are mixed in a linear network made up of resistors, does amplitude modulation take place?

3. What is the purpose of L_1 and C_1 in Figure 1-3?

4. The L_1C_1 resonant circuit of Figure 1-3 should have an extremely high Q. True or False?

5. To obtain amplitude modulation, two signals of different frequencies are mixed in a (a) nonlinear device, (b) linear device.

6. How does the amplitude of the modulating signal affect the height of the sideband signals of Figure 1-7?

7. What bandwidth is required to transmit a 27-MHz carrier that has been amplitude modulated by a 1-kHz modulating signal to provide radio control of a model airplane?

8. The carrier frequency of the transmitter of Practice Exercise 7 is changed to 51 MHz. The modulating frequency remains 1 kHz. What is the bandwidth required to transmit this signal?

9. What would the percentage of modulation be in Figure 1-8C if $Y = 5$ units and $X = 3$ units?

10. Percentages of modulation as high as 125% are normally used in AM modulation. True or False?

11. For conventional amplitude modulation, the bandwidth of the upper and lower sidebands is (a) always the same, (b) often the same, (c) never the same.

12. How many pairs of sideband signals are produced when three different audio signals modulate a carrier?

13. The unmodulated r-f carrier power of a radio station is 50 kW. What is the total sideband power and what is the power in each sideband at 100% modulation using a sinusoidal audio signal?

14. If the unmodulated r-f carrier power of a low-power broadcast station is 100 watts, the total radiated power at 100% modulation with a sinusoidal audio signal would be (a) 50 watts, (b) 100 watts, (c) 150 watts.

15. In the direct method of power measurement, the plate circuit power of the output stage is multiplied by an efficiency factor. True or False?

16. How is the input power of the final stage of a transmitter determined?

17. High-level modulation in the transmitter of a "walkie talkie" takes place in (a) any stage preceding the plate or collector circuit of the final r-f amplifier, (b) the plate or collector circuit of the final stage that feeds the antenna.

18. Where could low-level modulation take place in the transmitter of the "walkie talkie" referred to in Practice Exercise 17?

19. The microphone amplifier of a typical transmitter supplies the audio signal to the final r-f amplifier where modulation takes place. The r-f amplifier is therefore called the modulator and the microphone amplifier is called the modulated stage. True or False?

20. Less audio power is required to modulate an r-f carrier in low-level modulation than in high-level modulation. True or False?

21. Plate modulation of the final r-f stage in a Citizens Band transmitter is a popular form of (a) low-level modulation, (b) high-level modulation.

22. When the plate voltage of the modulated amplifier decreases to zero during one alternation of the a-f signal and increases to twice the plate supply voltage during the next alternation, the modulation percentage equals (a) 0%, (b) 50%, (c) 100%.

23. Suppose that you were designing an AM transmitter for use on the Amateur Radio bands. If high-level modulation is to be used, what class of operation could you use for greatest efficiency in the intermediate r-f amplifiers?

24. With suppressor grid modulation, the suppressor grid can be connected directly to the cathode. True or False?

Transistorized Modulation Circuits

For many years, commercial AM broadcast stations used vacuum tubes instead of transistors because of the higher power available. However, transistor circuits are presently replacing the older tube circuits because transistors with high-power capabilities are now available. Both high- and low-level modulation can be obtained using methods similar to those described for vacuum tubes in the previous sections of this lesson.

Two types of transistorized modulation circuits are shown in Figure 1-17. **EMITTER MODULATION** is shown in Figure 1-17A. An a-f modulating signal is applied to the emitter circuit, while the r-f carrier is applied to the base circuit. The a-f signal aids and opposes the voltage on the emitter, resulting in changes in the base-to-emitter bias voltage. These changes cause corresponding changes in the current through the collector circuit, resulting in an amplitude-modulated carrier output.

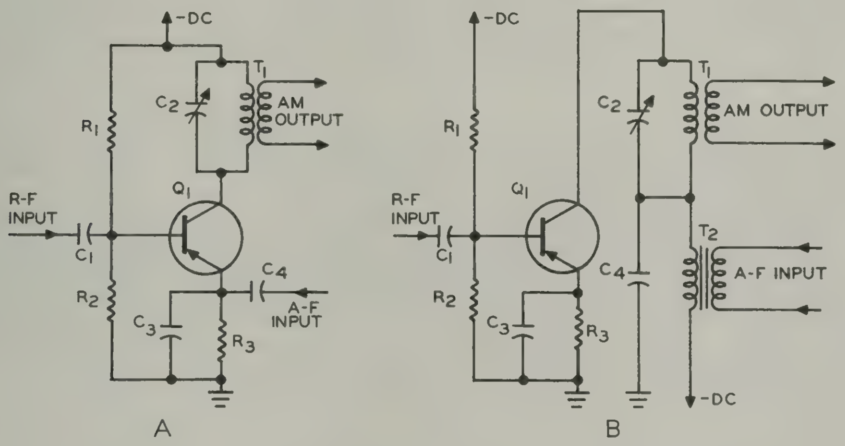


Figure 1-17

Figure 1-17B shows **COLLECTOR MODULATION**. This type of modulation is similar to plate modulation of a vacuum tube. The a-f signal is applied to the collector circuit through the modulation transformer, T_2. This signal alternately aids and opposes the collector voltage. Variations in the collector voltage cause changes in collector current, resulting in an amplitude-modulated carrier output.

Either the emitter or collector modulation circuit just described can be used in the transmitter circuit shown by the block diagram of Figure 1-18. This transmitter uses low-level modulation. The r-f section consists of an r-f oscillator, buffer amplifier, modulated amplifier and power amplifier. The a-f section contains a low-frequency voltage amplifier and a low-power modulator stage.

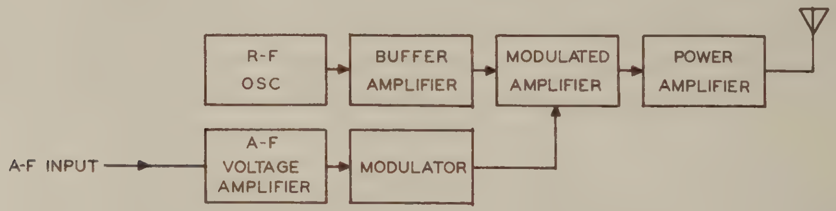


Figure 1-18

The modulating signal is applied to the modulated amplifier, where modulation takes place. The amplifier stage can be operated Class C for greatest efficiency. However, the following stages must be operated with very little distortion. This generally requires Class B or a more distortion-free class of operation.

TYPES OF TRANSMISSION

In standard AM radio broadcasting, both sidebands are transmitted just as they are produced at the output of the modulated amplifier. This type of transmission is known as **DOUBLE SIDEBAND TRANSMISSION (DS)**. The information transmitted is contained within both the upper and lower sidebands. Each sideband contains the same information that is in the other. THE CARRIER DOES NOT CONTAIN INFORMATION IN AM.

Since the carrier acts merely as a reference for the sidebands, it is possible to remove the carrier from the transmitted r-f signal and still transmit the intelligence. This type of transmission is called **DOUBLE SIDEBAND SUPPRESSED CARRIER TRANSMISSION (DSSC)**. For a receiver to recover the information in the sidebands, a carrier must be reinserted. This is done by generating a low-level carrier signal at the receiver. The reinserted carrier has to have the exact frequency and phase as the original carrier if distortion is to be avoided.

If only one sideband is transmitted, information can still be transmitted because each sideband, at any instant, contains the same information as the other sideband. This system is known as **SINGLE SIDEBAND TRANSMISSION (SSB)**.

SUPPRESSED CARRIER TRANSMISSION

In conventional AM broadcast transmission, there is more power in the carrier than in both sidebands. Since no carrier is transmitted in suppressed carrier transmission, less transmitter power is required. If the carrier is not transmitted, the sideband power can be increased without increasing the size of the transmitter.

As an example, consider a 100-watt carrier that is 100% modulated. Since 50 watts are contained in the sidebands, the total transmitted power is 150 watts. If the carrier is suppressed, the sideband power can be increased to 150 watts without changing the transmitted power. This 150 watts represents useful power, since none of it is being used for the carrier.

One system for suppressing a carrier signal and obtaining modulated sidebands involves a circuit called a **BALANCED MODULATOR**. Balanced modulators take different forms, but they all serve the same basic purpose. These circuits produce both upper and lower sideband frequencies but greatly suppress the carrier. The transmission of color television often uses a balanced modulator to suppress the color subcarrier.

Figure 1-19 shows a circuit which illustrates the operation of a balanced modulator. Tubes V_1 and V_2 have identical characteristics. Notice that there are two signal sources in the grid circuit of each tube. One source is the secondary of T_2. The other is half the secondary of T_1—the upper half for V_1 and the lower half for V_2. Thus, the output of either V_1 or V_2 depends on both the r-f input and the modulating signal (a-f input).

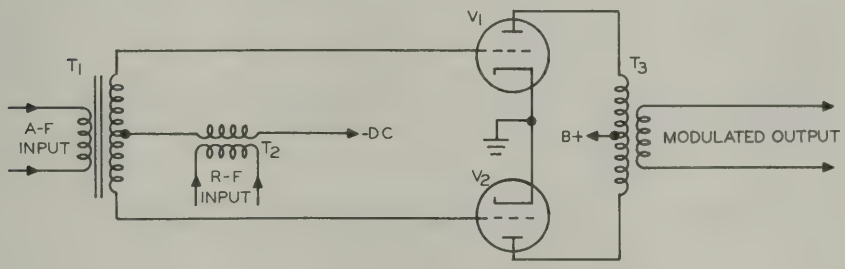


Figure 1-19

The r-f input is coupled through T_2 to the grids of both V_1 and V_2. As a result, the r-f signal is applied to the grids in phase. The a-f signal or modulating signal is coupled to V_1 and V_2 in push-pull fashion. When the modulating signal drives the grid of V_1 less negative, it drives the grid of V_2 more negative. On the other alternation, the opposite occurs. Thus, the modulating signal is applied to the grids 180° out-of-phase.

Since the r-f signals applied to the grids of V_1 and V_2 are of the same phase and amplitude, the resulting changes of V_1 and V_2 plate currents oppose and cancel each other in T_3. Therefore, the output of the balanced modulator at the carrier frequency is zero.

The modulating signals at the grids of V_1 and V_2 are 180° out-of-phase. Thus, when the V_1 plate current increases due to a modulating signal, the V_2 plate current decreases due to the modulating signal. Thus, there is an increase in the current passing downward in the upper half of T_3, and a decrease in the current passing upward in the lower half of T_3. The result is an additive effect as far as the current change in the entire T_3 primary winding is concerned. On the other alternation of the modulating signal, these conditions reverse. V_1 and V_2 are operated in nonlinear fashion by proper selection of the grid bias voltage (−DC). As a result, the increase of plate current in one tube is greater than the decrease of plate current in the other tube.

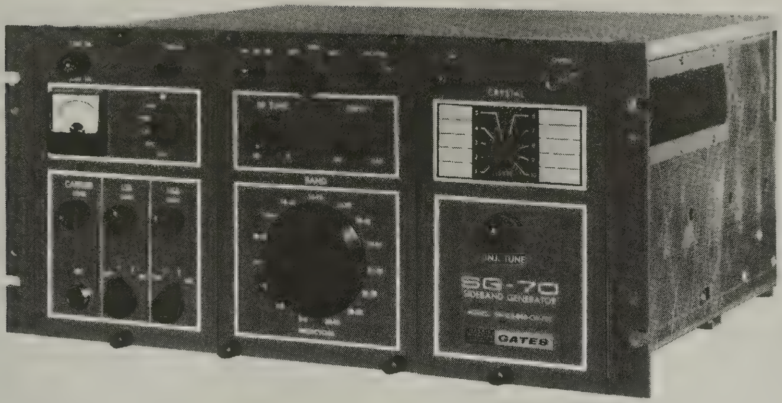
When both a modulating signal and an r-f carrier signal are fed into the grid circuit, sidebands are produced. We have stated that when two frequencies are fed into a modulator it is possible to get four frequencies out. These signals are the two original frequencies and the upper and lower sidebands. We have shown how the carrier is removed by cancellation in T_3. This leaves only the sidebands and the modulating signal. The modulating signal is filtered out because of the low impedance that the T_3 primary has at this frequency. This leaves only the two sidebands at the output of T_3.

Suppressed carrier transmission is used in some forms of communications. For example, it is used in both color television and in frequency-modulated stereo broadcasts. The color subcarrier in TV is suppressed in a balanced modulator to produce a double sideband suppressed carrier signal. The multiplex subcarrier used in stereo FM is also suppressed in a balanced modulator to produce a double sideband suppressed carrier signal.

SINGLE SIDEBAND TRANSMISSION

The information contained in both the upper and lower sidebands is identical at any given instant. To transmit information, only one sideband is really needed. Thus, the carrier and also one sideband can be suppressed. Single sideband transmission can be obtained using a balanced modulator to remove the carrier; then, either the upper or lower sideband is suppressed and the remaining sideband is transmitted.

This system has two advantages over the double sideband suppressed carrier transmission system. The bandwidth of the transmitted signal is



This sideband generator produces crystal controlled AM, SSB and other signals. At the transmitter, it is followed by linear amplifiers to produce a higher power output signal.
Courtesy Gates Radio Co.

reduced because only one sideband is used. Also, the sideband power can be increased without increasing the total transmitted power. Therefore, if a station is allowed a certain amount of transmitted power, all of this power can be put into the one sideband.

It should be stressed that this system of transmission uses less of the frequency spectrum. This produces less interference in crowded communication channels. For this reason, single sideband transmission is finding increased use in communications, especially amateur radio.

A block diagram of a single sideband transmitter is shown in Figure 1-20. For simplicity, only five blocks are shown. The upper left block represents the r-f section supplying the carrier. The series of amplifiers used to increase the audio signal to the level required by the modulated stage are shown by the single block marked a-f section. The output of the r-f section and the output of the a-f signal section are applied to the balanced modulator.

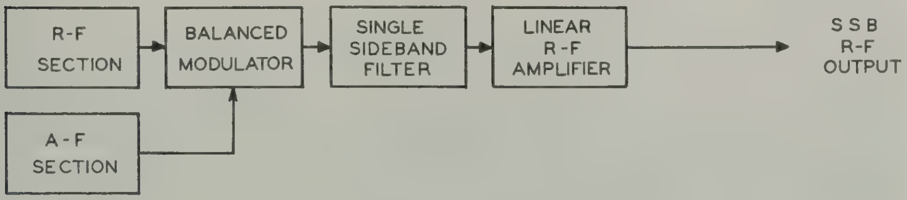


Figure 1-20

The original r-f carrier signal is suppressed by the balanced modulator. Only the upper and lower sidebands appear in the output of this stage. To remove

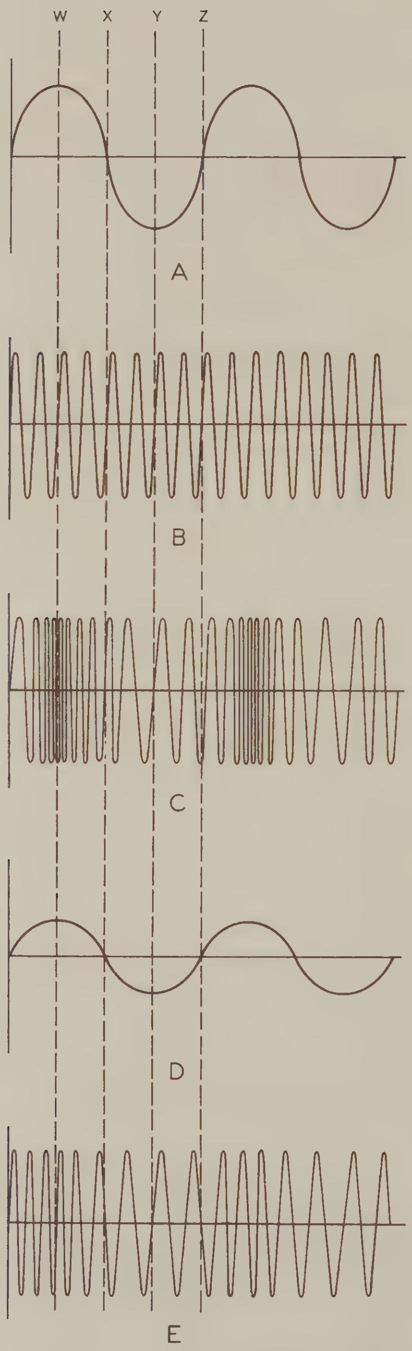


Figure 1-21

one of the sidebands, the output of the balanced modulator is applied to a special filter network. This filter network is designed to pass the band of frequencies of one sideband, while removing the other sideband. The output of the filter network is a single sideband—either the upper sideband or the lower sideband.

A single sideband signal is usually generated at a comparatively low-power level. Therefore, a linear amplifier block follows the filter of Figure 1-20. This may contain a number of stages of amplification, depending on the desired output power level to the antenna.

BASIC THEORY OF FM

In FM, the modulating signal varies the frequency of the r-f carrier. As the instantaneous amplitude of the modulating signal changes, the frequency of the r-f carrier changes. However, the amplitude of the carrier does not change. The frequency of the modulating signal determines the rate of carrier frequency change.

Figure 1-21 shows the principles of frequency modulation. The modulating signal is shown in Figure 1-21A and the r-f carrier in Figure 1-21B. As in most modulation systems, the r-f carrier frequency must be higher than the highest modulating signal frequency. For this explanation, assume that the modulating signal is 1000 Hz and the r-f carrier is 1 MHz.

Figure 1-21C shows the resultant frequency-modulated r-f carrier. Notice that as the modulating signal increases to its maximum positive value (point W), the carrier frequency increases (the waves bunch up). Then, as the modulating signal drops back to zero (point X), the carrier frequency returns to its original value. As the modulating signal increases to its maximum negative value (point Y), the carrier frequency decreases (the waves spread out). Finally, as the modulating signal returns to zero (point Z), the carrier frequency returns to its original value.

Therefore, as the modulating signal goes positive and negative, the carrier frequency deviates above and below its original value. The amount of carrier frequency change is referred to as **FREQUENCY DEVIATION** or **CARRIER DEVIATION.** The unmodulated carrier frequency is referred to as the **CENTER FREQUENCY**.

The AMOUNT of carrier deviation is proportional to the AMPLITUDE of the modulating signal. Maximum carrier deviation occurs at the peaks of the modulating signal. Figure 1-21D shows a modulating signal with half the amplitude of that of Figure 1-21A. The resultant frequency-modulated r-f carrier is shown in Figure 1-21E. Remember, the greater the amplitude of the modulating signal, the greater the carrier deviation.

Suppose that the modulating signal of Figure 1-21A causes a carrier deviation of ±.1 MHz. With a center frequency of 1 MHz, the carrier frequency is 1.1 MHz at point W in Figure 1-21C and .9 MHz at point Y.

Since the modulating signal amplitude in Figure 1-21D is reduced by one-half, the resulting carrier deviation in Figure 1-21E is also reduced by one-half. One-half of .1 MHz is .05 MHz. Thus, the carrier frequency is 1.05 MHz at point W in Figure 1-21E and .95 MHz at point Y.

The RATE of carrier deviation depends on the FREQUENCY of the modulating signal. Figure 1-22 shows the effects of modulating signal frequency. Figures 1-22A, B and C are the same as Figures 1-21A, B and C. With a modulating signal frequency of 1 kHz, the carrier deviates above and below its center frequency 1000 times per second. In Figure 1-22D, the modulating frequency is doubled (2 kHz). Notice in Figure 1-22E that the carrier deviates twice as often as in Figure 1-22C. With a modulating frequency of 2 kHz, the carrier deviates above and below its center frequency 2000 times a second. Note that the modulating frequency affects the rate of deviation, not the amount of deviation.

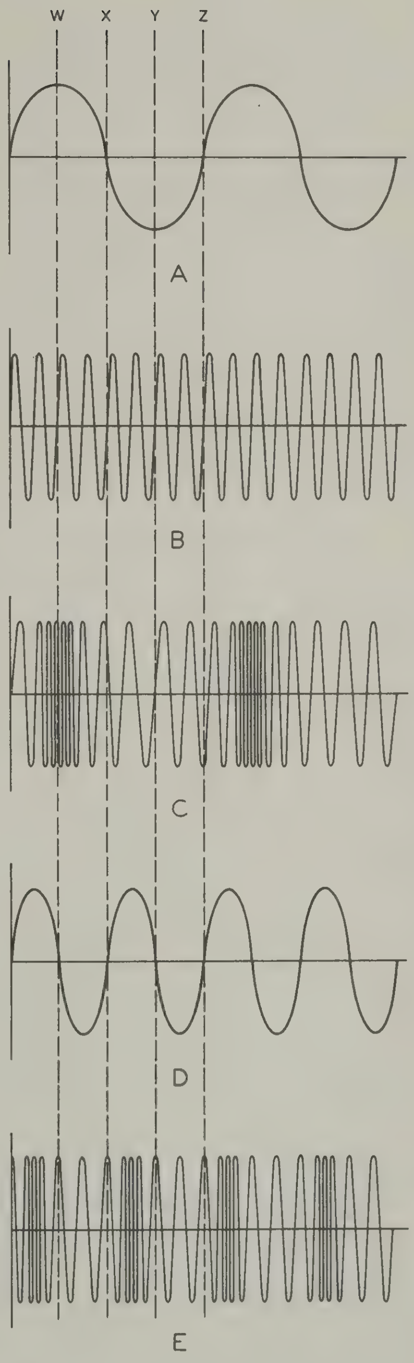


Figure 1-22

The principles of frequency modulation can be summed up as follows:

1. In FM the AMOUNT of carrier deviation (frequency deviation) is proportional to the modulating signal AMPLITUDE.
2. In FM the RATE of carrier deviation (frequency deviation) is the same as the modulating signal FREQUENCY.
3. In FM the AMPLITUDE of the total radiated power REMAINS CONSTANT.

FM MODULATION PERCENTAGE

When an r-f carrier is frequency modulated, it is forced to deviate above and below its center frequency. The carrier deviation is directly proportional to the modulating signal amplitude. Theoretically, 100% modulation occurs when the carrier is made to deviate from zero frequency to twice its center frequency. For example, a 1-MHz carrier would deviate from 0 Hz to 2 MHz at 100% modulation. A 2-MHz carrier would deviate from 0 Hz to 4 MHz. Thus, 100% modulation would cause a different amount of carrier deviation for different carrier frequencies.

You can see how impractical this modulation requirement would be in terms of bandwidth. Therefore, 100% modulation is defined as some particular deviation, regardless of carrier frequency. The actual carrier deviation designed as 100% modulation depends on the particular communications service.

In the FM broadcast band (88–108 MHz), 100% modulation produces a carrier deviation of ±75 kHz from the center frequency. As another example, the FM sound carrier of a TV station is limited to a carrier deviation of ±25 kHz for 100% modulation.

In the 25–50 MHz and 150–174 MHz two-way communications band, the carrier deviation is only ±5 kHz for 100% modulation. A communications service with a small carrier deviation such as this is referred to as **NARROW BAND FM.**

The maximum carrier deviation for the various communications services in the United States is assigned by the FCC. The carrier deviations are chosen so that the desired number of stations can operate without interfering with each other. Other countries have similar regulating organizations.

Reducing the carrier deviation to below that specified for 100% modulation is a reduction in the MODULATING PERCENTAGE. For example, in the 88–108 MHz FM broadcast band, ±75 kHz deviation is 100% modulation. A deviation of ±37.5 kHz (half of 75 kHz) is 50% modulation, and so on.

FM SIDEBANDS

Whenever a carrier is modulated, additional signals are produced. These signals are grouped slightly above and below the carrier frequency and are called **SIDEBANDS**. The sidebands, produced by the modulation process, contain the intelligence that is being transmitted. The intelligence is recovered from the sidebands at the receiver.

When a carrier is frequency modulated, a large number of sideband signals are produced. However, the signals far from the carrier frequency have so little amplitude that they can be disregarded.

Figure 1-23A shows the result of frequency modulating a carrier with a 15-kHz sinusoidal signal. The first lower sideband signal is 15 kHz below the carrier while the first upper sideband is 15 kHz above the carrier. These two sideband signals, spaced equally above and below the carrier, are called a

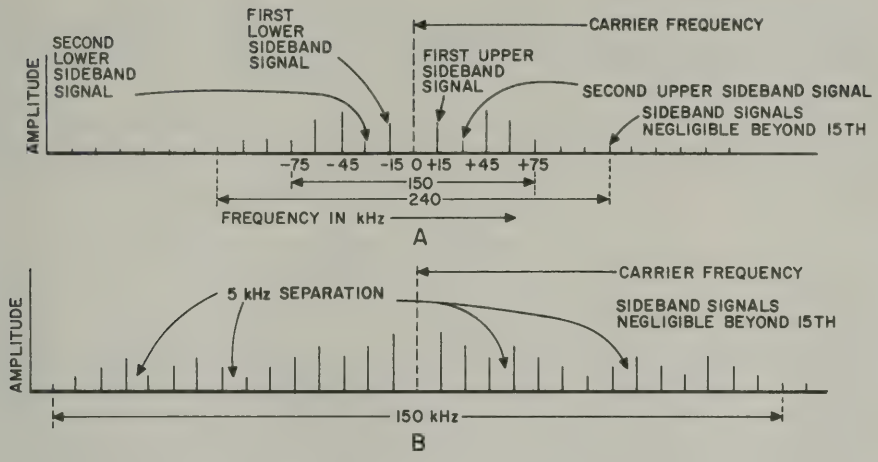

FIRST LOWER SIDEBAND SIGNAL
SECOND LOWER SIDEBAND SIGNAL
AMPLITUDE
CARRIER FREQUENCY
FIRST UPPER SIDEBAND SIGNAL
SECOND UPPER SIDEBAND SIGNAL
SIDEBAND SIGNALS NEGLIGIBLE BEYOND 15TH
-75
-45
-15
0
+15
+45
+75
150
240
FREQUENCY IN kHz
A
5 kHz SEPARATION
CARRIER FREQUENCY
SIDEBAND SIGNALS NEGLIGIBLE BEYOND 15TH
AMPLITUDE
150 kHz
B

Figure 1-23

SIDEBAND PAIR. The second sideband pair is 30 kHz above and below the carrier. This places the second sideband pair 15 kHz away from the first pair. The separation between adjacent sideband signals is determined by the frequency of the modulating signal. For example, in Figure 1-23A, the separation is 15 kHz.

Figure 1-23B shows the results of frequency modulating a carrier with a 5-kHz sinusoidal signal. Notice here that the sideband signals are 5 kHz apart.

The energy in each sideband pair does not decrease uniformly as the separation from the carrier is increased. For example, the fourth sideband pair in Figure 1-23B has greater amplitude than the third sideband pair. A point is reached, however, where the outermost sideband signals contain so little energy that they can be disregarded. This point is determined by a factor called the **MODULATION INDEX.**

The modulation index is the ratio of the carrier frequency deviation to the modulating signal frequency. This is shown below.

$$\text{Modulation Index} = \frac{\text{Carrier Frequency Deviation}}{\text{Frequency of Modulating Signal}} \qquad (3)$$

Assume that 100% modulation causes a carrier frequency deviation of ±75 kHz and the modulating signal frequency is 5 kHz. We can use these values in the formula to find the modulation index:

$$\text{Modulation Index} = \frac{75}{5} = 15.$$

Regardless of the percentage of modulation or the modulating signal frequency, the modulation index is calculated in the same manner. For example, suppose that the 5-kHz modulating signal has only enough amplitude to cause 40% modulation. This produces a carrier deviation of 40% of ±75 kHz, or ±30 kHz. The modulation index is then as shown below:

$$\text{Modulation Index} = \frac{30}{5} = 6.$$

The importance of the modulation index is its relationship to the bandwidth required to transmit an FM signal. The bandwidth must be wide enough to include all sideband signals that contain a significant amount of power (at least 1% of the unmodulated carrier power). The number of significant sideband pairs is dependent upon the modulation index. Information on the number of significant sideband pairs for various values of modulation index is given later in this lesson.

The bandwidth of an FM signal is determined partly by the modulating signal frequency. The modulating signal frequency is used to determine the modulation index and, in turn, the number of significant sideband pairs. Increasing the modulating signal frequency decreases the modulation index and the number of significant sideband pairs. However, although fewer sideband pairs exist, they are separated further from the carrier; therefore, the increase in modulating signal frequency increases the bandwidth. Likewise, a decrease in the modulating signal frequency decreases the bandwidth.

RADIATED POWER

When an r-f carrier is frequency modulated, power is transferred from the carrier to the sidebands. The power removed from the carrier is such that the sum of the carrier and sideband powers remains constant. Thus, the total radiated power remains constant. This is unlike an AM system, where the total radiated power varies with the percentage of modulation.

MODULATOR SYSTEMS

There are two basic systems which are used to produce a frequency-modulated signal. In the **DIRECT FM** system, modulation takes place in the master oscillator stage. In the **INDIRECT FM** system, the signal from an oscillator is fed to another stage, where frequency modulation occurs. The oscillator itself is not modulated in the indirect FM system.

The following Practice Exercise questions cover the subjects which you have just studied. They are:

MODULATION CIRCUITS

CONTROL GRID MODULATION

TRANSISTORIZED MODULATION CIRCUITS

TYPES OF TRANSMISSION

SUPPRESSED CARRIER TRANSMISSION

SINGLE SIDEBAND TRANSMISSION

BASIC THEORY OF FM

FM MODULATION PERCENTAGE

FM SIDEBANDS

RADIATED POWER

25. Why might control grid modulation be used rather than plate modulation in a taxicab mobile transmitter?

26. Low-level modulation cannot be used in a transistorized, low-power, aviation radio transmitter. True or False?

27. Assume that two mobile radio transmitters have the same output power. One uses high-level modulation and the other low-level modulation. Which modulator must provide the least amount of power for 100% modulation?

28. Which class of operation is often used for the modulated amplifier of Figure 1-16 or 1-18?

29. What is one advantage of DSSC transmission over conventional AM transmission?

30. What type of circuit might you expect to find used to suppress the color subcarrier in color TV transmission?

31. The output of a balanced modulator is (a) a carrier signal without sidebands, (b) a carrier and both sidebands, (c) both sidebands without a carrier.

32. The transmitter circuitry of a single sideband transmission is more complicated than the circuits used in a standard double sideband system. True or False?

33. An important advantage of single sideband transmission is (a) the decreased signal-to-noise ratio, (b) the increased power needed for modulation, (c) the smaller space required in the frequency spectrum.

34. Only one sideband is required to transmit information. True or False?

35. A filter network is used in a single sideband transmitter to remove one of the sidebands. True or False?

36. How does most electrical interference affect a radiated r-f carrier?

37. What characteristic of an r-f carrier is varied in an FM communications system?

38. In FM, the amount of carrier deviation (frequency deviation) is determined by the modulating signal (a) amplitude, (b) frequency.

39. How does the modulating signal amplitude affect the carrier amplitude in FM?

40. In FM, the rate of carrier deviation (frequency deviation) is determined by the modulating signal (a) amplitude, (b) frequency.

41. Increasing the modulating signal frequency increases the amount of carrier deviation. True or False?

42. Why is the carrier deviation limited to a specific amount in various FM communications services?

43. What is the maximum carrier deviation in the FM broadcast band (88–108 MHz)?

44. In the 150–174 MHz two-way communications service, 100% modulation is a carrier deviation of (a) ±37.5 kHz, (b) ±1.7 MHz, (c) ±5 kHz.

45. The carrier deviation for 50% modulation of a TV station sound carrier is ±12.5 kHz. True or False?

46. When a carrier is frequency modulated, only one sideband signal is produced. True or False?

47. If a 4-kHz sinusoidal signal frequency modulates a carrier, what is the separation between the sideband signals?

48. In Figure 1-23A, how far (in terms of frequency) is the third lower sideband signal from the carrier?

49. For what purpose is the modulation index used?

50. Suppose that the carrier deviation of an FM wave is 25 kHz and that the modulation signal frequency is 10 kHz. What is the modulation index?

51. When the modulating signal frequency increases, the bandwidth of an FM station (a) increases, (b) decreases, (c) remains the same.

52. What happens to the total radiated power of an FM station during modulation?

Direct FM

Figure 1-24 shows the simplified block diagram of a direct FM system. The system is for an FM broadcast station (88–108 MHz). The modulating signal is an audio signal. This signal is amplified and applied to the modulator stage. The output of the modulator stage is used to deviate the master oscillator frequency. The frequency-modulated output from the master oscillator is then amplified and applied to the antenna system.

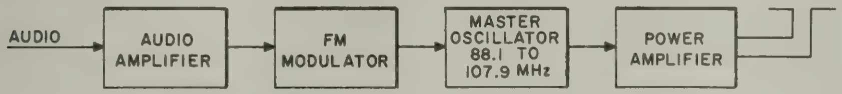


Figure 1-24

Notice that in Figure 1-24 the master oscillator is operating at the carrier frequency. Since most carrier frequencies are quite high, oscillator frequency stability can be a problem. Very small changes in component or circuit characteristics can cause an appreciable shift in the oscillator center frequency. This causes serious difficulty in the reception of the signal.

Another requirement of the direct FM system shown in Figure 1-24 is that the master oscillator must deviate the full amount required for the particular communications service. For example, the master oscillator must deviate ±75 kHz at 100% modulation when used in an FM broadcast system. In actual equipment, it is difficult to produce these large deviations and still maintain linearity. For example, if a 1-volt signal applied to the modulator causes a deviation of ±5 kHz, a 2-volt signal should produce a deviation of ±10 kHz and so on. Actually, the 2-volt signal may only produce a deviation of ±9 kHz.

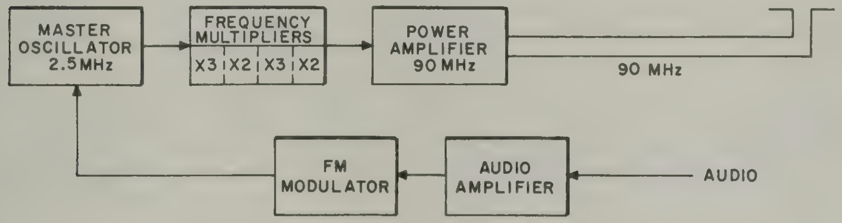


Figure 1-25

The difficulties of the simple system shown in Figure 1-24 can be overcome by using the arrangement shown in Figure 1-25. Here, the master oscillator operates at a frequency below the carrier frequency. The output of the master oscillator is fed to a group of **FREQUENCY MULTIPLIERS**. The frequency multipliers increase the master oscillator frequency to the desired carrier frequency, 90 MHz in this example.

A frequency multiplier is an amplifier circuit which has its output circuit tuned to a harmonic of the input circuit. As a result, the output frequency is a harmonic (multiple) of the input frequency. For example, a frequency doubler has its output circuit tuned to the second harmonic of its input circuit. A frequency tripler has its output circuit tuned to the third harmonic of its input circuit.

The first frequency multiplier in Figure 1-25 is a tripler (×3). Since the master oscillator frequency is 2.5 MHz, the output of the first frequency multiplier is 3 × 2.5, or 7.5 MHz. The 7.5-MHz signal is then fed to a doubler (×2). The output of the doubler is 2 × 7.5, or 15 MHz. The next tripler increases the frequency to 3 × 15, or 45 MHz. Finally, the last doubler increases the frequency to the desired carrier frequency of 90 MHz.

With the frequency multiplier system, the master oscillator can be operated at a low, stable frequency. Any desired carrier frequency can be obtained by using frequency multipliers.

In addition to multiplying the master oscillator frequency, the frequency multipliers multiply the amount of master oscillator frequency deviation. Suppose that at 100% modulation the master oscillator frequency deviation of Figure 1-25 is ±2 kHz. The frequency multipliers provide a total multiplication of 3 × 2 × 3 × 2, or 36. The resultant carrier frequency deviation is 36 × 2, or ±72 kHz. Thus, the master oscillator need only be deviated a small amount. As a result, the linearity is improved and distortion is reduced.

Even though the master oscillator operates at a low frequency in the direct FM system of Figure 1-25, frequency stability is still a problem. To further improve stability, an **AUTOMATIC FREQUENCY CONTROL (AFC)** system is used.

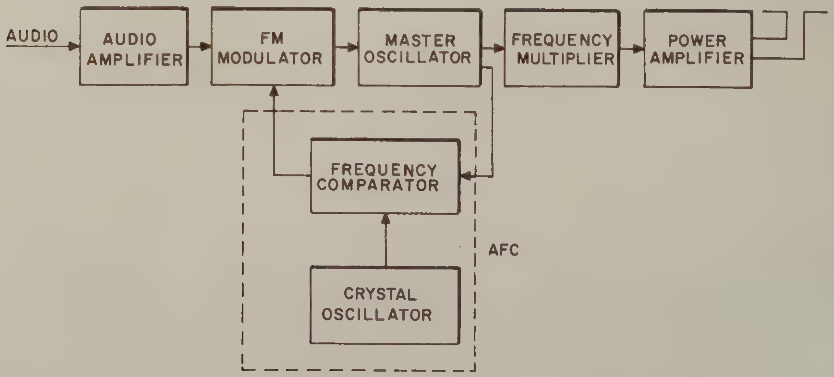


Figure 1-26

Figure 1-26 is the block diagram of a direct FM system with AFC. The AFC system compares the master oscillator center frequency with a very accurate and stable crystal oscillator. Any change in the master oscillator center frequency is detected and a correction signal is sent to the modulator. The correction signal returns the master oscillator to the correct frequency.

Indirect FM

In an indirect FM system, the master oscillator is operated at a constant frequency. Frequency modulation takes place in another stage. With this arrangement, a fixed-frequency, highly stable, master oscillator can be used.

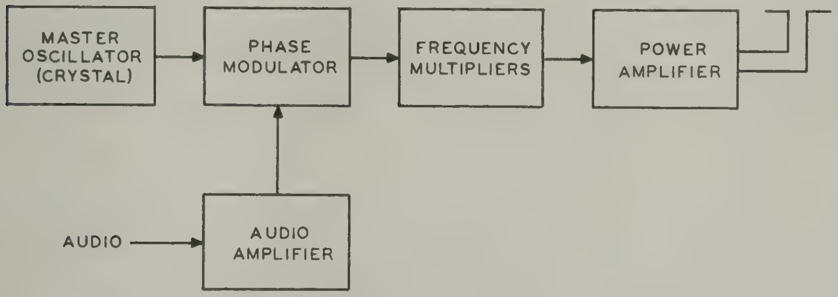


Figure 1-27

Figure 1-27 shows the block diagram of an indirect FM system. Frequency modulation is obtained by using the modulating signal to shift the PHASE of the r-f signal developed by the master oscillator. This type of modulation is known as **PHASE MODULATION (PM)**.

When an r-f signal is phase modulated, its frequency deviates in proportion to both the amplitude and frequency of the modulating signal. However, for true FM, the amount of deviation must be proportional to only the amplitude of the modulating signal. For the desired type of FM, a correction circuit must be added so that the frequency deviation is proportional to only the modulating signal amplitude. This correction circuit is called the **AUDIO CORRECTOR**.

Figure 1-28 shows how phase modulation produces frequency modulation. The modulating signal is shown in Figure 1-28A. The dashed waveform of Figure 1-28B represents the unmodulated r-f signal from the master oscillator. The solid waveform is the phase-modulated r-f signal.

At the left of Figure 1-28A, the modulating signal is increasing to its maximum positive value. The phase modulator causes the phase of its

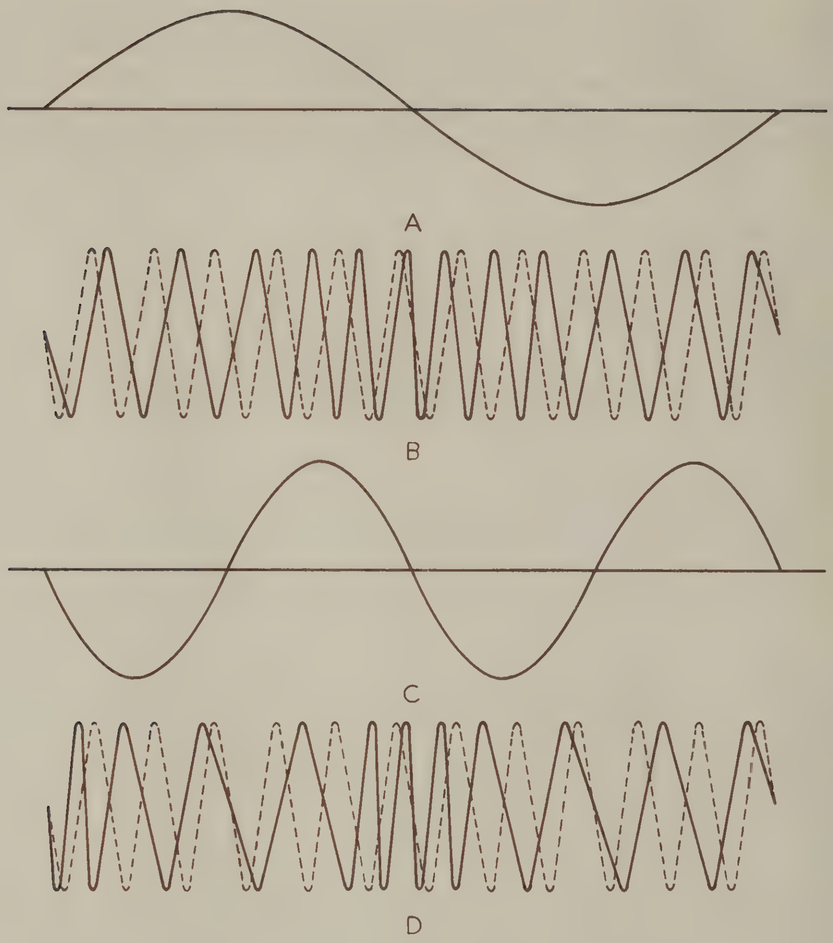


Figure 1-28

output signal to lag the signal from the master oscillator. This is shown in Figure 1-28B by the spreading out of the solid waveforms (modulated signal). The spreading out causes the cycles of the modulated signal to lag the unmodulated signal. The spreading out of the cycles also represents a decrease in frequency. As the modulating signal decreases to zero, the amount of lag decreases until the modulated signal is in phase with the master oscillator signal.

The opposite action occurs on the negative alternation of the modulating signal. The negative alternation causes the modulated signal to lead the output of the master oscillator. This, in turn, produces an increase in frequency.

In Figure 1-28C, the modulating signal frequency has been increased. This affects the frequency deviation, as shown in Figure 1-28D. With an increase in the modulating signal frequency, the phase must change more rapidly. To accommodate this, the modulated signal cycles spread out and bunch up more. As a result, the frequency deviation increases. This undesired increase is compensated for by the audio corrector circuit in the transmitter. The result is a frequency-modulated signal, where the frequency deviation depends only on the modulating signal amplitude.

Reactance Tube Modulator

One direct FM system used to frequency modulate a carrier is the **REACTANCE TUBE MODULATOR**. Figure 1-29 shows the circuit of a reactance tube modulator and the master oscillator it controls. The reactance tube modulator, V_1, is to the left of the dashed line. To the right of the dashed line is V_2, a Hartley oscillator. Grid leak bias for V_2 is provided by R_3 and C_6. L_3 and C_7 form a decoupling circuit which prevents r-f from being coupled back to the power supply.

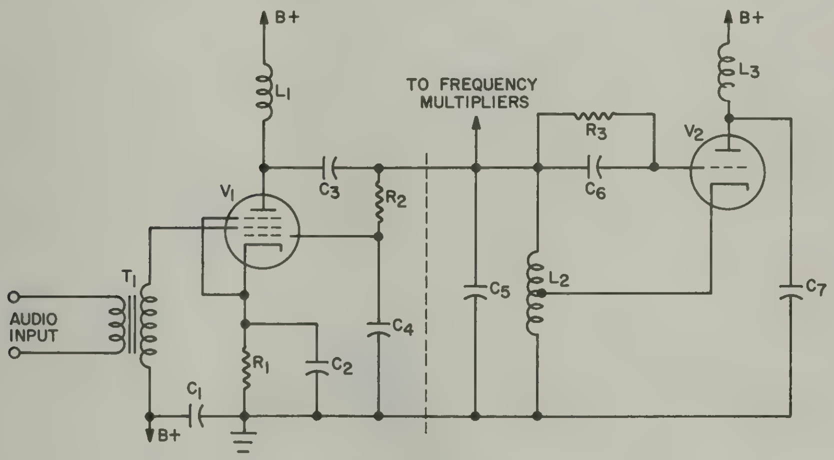


Figure 1-29

The V_1 reactance tube modulator connected across (in parallel with) the C_5L_2 tank circuit acts like an inductance that is controlled by the modulating signal. The modulating signal is fed to the screen grid of V_1 through T_1. Therefore, the inductance of V_1 varies in step with the modulating signal. The changing V_1 inductance varies the resonant frequency of the C_5L_2 tank circuit. Thus, the reactance tube modulator varies the frequency of the master oscillator according to the modulating signal.

Let's examine the operation of the V_1 circuit in greater detail. The r-f signal developed by the V_2 oscillator circuit appears across C_5 and L_2. This r-f signal is coupled to the plate circuit of V_1 through C_3. The r-f signal is also applied to the control grid of V_1 through the R_2C_4 network. The values of R_2

and C_4 are chosen so that the r-f voltage at the control grid of V_1 lags the r-f voltage coupled to its plate by 90°.

The plate current variations of a vacuum tube are in phase with the control grid voltage variations. Therefore, since the V_1 control grid voltage lags the r-f voltage at the plate, the V_1 plate current also lags the V_1 r-f plate voltage. Whenever the current through a device lags the voltage across it, the device presents the effect of an inductance. Thus, V_1 acts as an inductance in parallel with C_5 and L_2.

The V_1 screen grid is connected to B+ through the secondary of T_1. The audio input, or modulating signal, connected to the primary of T_1, causes a variation in the V_1 screen voltage. When the modulating signal drives the V_1 screen voltage more positive, the plate current variations increase in amplitude. On the other alternation of the modulating signal, the V_1 screen voltage becomes less positive, thus decreasing the amplitude of the plate current variations.

This FM transceiver operates in the 118–136 MHz band and is used for two-way communications between aircraft and ground service stations.

Courtesy Communications Co., Div. of E. F. Johnson

An increase of V_1 plate current appears as a decrease of inductance across C_5. This causes an increase in the frequency developed by V_2. A decrease of V_1 plate current appears as an increase of inductance across C_5 and causes a decrease in the frequency developed by V_2.

The modulating signal thus varies the inductance presented by the V_1 circuit to the L_2C_5 tank. This, in turn, varies the frequency of the r-f signal developed by V_2. The frequency-modulated signal appearing across C_5 and L_2 is applied to the frequency multipliers in the transmitter.

A reactance tube circuit can be designed so that it appears as a variable capacitance. This can be done in the circuit of Figure 1-29 by interchanging the positions of R_2 and C_4 and changing their values to provide the desired results.

Serrasoid Phase Modulator

Figure 1-30 shows the block diagram of an indirect FM system called the **SERRASOID PHASE MODULATOR**. As mentioned earlier, the PM system has the advantage of increased stability. Modulation does not take place in the oscillator stage, but in a later stage. The disadvantage of a PM system is the small amount of frequency deviation produced. This requires the use of many multipliers to obtain the desired frequency deviation.

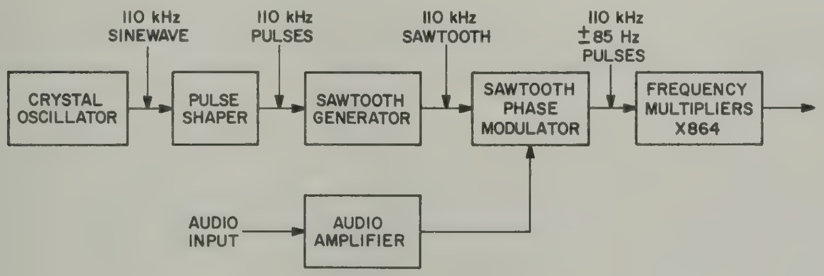


Figure 1-30

In the serrasoid PM system of Figure 1-30, the crystal oscillator develops a stable low-frequency sinusoidal signal, 110 kHz in this example. This sinusoidal signal is fed to a pulse shaper circuit. The pulse shaper is an overdriven amplifier that produces 110-kHz pulses. These pulses are used to trigger a sawtooth generator, which produces a 110-kHz sawtooth waveform.

The 110-kHz sawtooth is fed to the sawtooth phase modulator, which conducts only on the positive-going portions of the sawtooth. Also applied to the sawtooth phase modulator is the audio modulating signal. The modulating signal causes the modulator to conduct at different points on the sawtooth. The exact point at which the modulator conducts depends on the amplitude of the modulating signal. The final result is that 110-kHz phase-modulated pulses are produced.

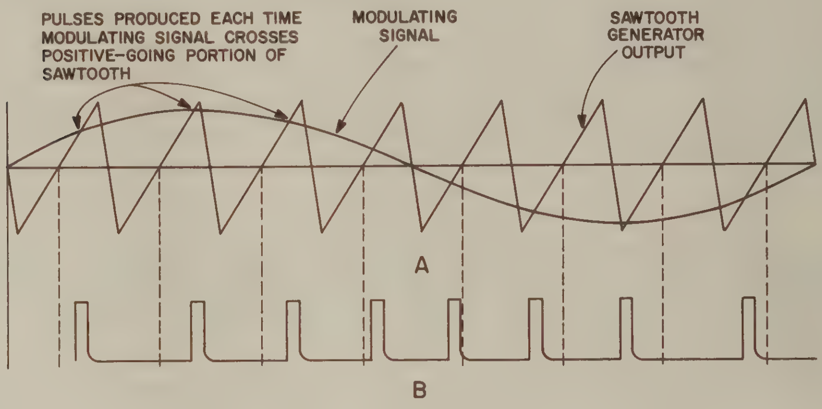

PULSES PRODUCED EACH TIME MODULATING SIGNAL CROSSES POSITIVE-GOING PORTION OF SAWTOOTH
MODULATING SIGNAL
SAWTOOTH GENERATOR OUTPUT
A
B

Figure 1-31

Figure 1-31 shows the waveforms in the serrasoid circuit. The modulating signal and sawtooth applied to the sawtooth phase modulator are shown in Figure 1-31A. Each time the modulating signal crosses the positive-going portion of the sawtooth, the sawtooth phase modulator develops an output pulse. These pulses are shown in Figure 1-31B. Notice that the spacing (phase) of the pulses varies with the modulating signal.

The pulses from the sawtooth phase modulator are then fed to a frequency multiplier. After multiplication, the pulses appear as a frequency-modulated r-f signal.

In Figures 1-28 and 1-31, we have taken liberty of exaggerating the amount of phase shift produced so that the change would be readily apparent. Actually, the amount of phase shift is very small. For example, the deviation of the 110-kHz pulses in Figure 1-30 is only ±85 Hz. The multiplier circuit in Figure 1-30 then multiplies the pulse frequency and the amount of frequency deviation 864 times. This results in a carrier center frequency of 110 kHz × 864, or about 95 MHz, and a carrier deviation of ±85 Hz × 864, or about ±73 kHz. These values are suitable for FM broadcasting. By choosing the proper crystal oscillator frequency and multiplication factor, any desired carrier frequency and deviation can be obtained.

STEREOPHONIC MULTIPLEXING

When we hear sound, we can usually tell the direction it is coming from. For example, if a number of people are involved in a conversation, we hear some

This stereo FM signal simulator is used for alignment of the stereo multiplex circuitry of an FM receiver.
Courtesy RCA-Electronic Components Div.

of the voices from our left, some from in front of us, etc. However, when sounds are broadcast by monophonic radio, or records are played on an monophonic phonograph, we tend to lose this sense of direction. All sounds come from a single point—the speaker of the radio or phonograph.

By using a two-channel recording or broadcasting system, some of the effects heard while listening to a live performance can be duplicated. The sounds we would hear with our left ear are picked up by one microphone, while the sounds we would hear with our right ear are picked up with another microphone. The two signals are kept separate and recorded or broadcast. In our home, we receive the two signals and amplify them separately. A two-channel sound system such as this is referred to as a STEREOPHONIC SYSTEM.

To transmit a stereophonic (two-channel) signal, a special system of transmission has been authorized by the FCC in the United States. The stereo signal is transmitted by FM broadcast stations, using a **MULTIPLEX**

TRANSMISSION system. This system involves the transmission of more than one modulating signal, using only one carrier.

Two microphones are among the equipment used to transmit a live stereo broadcast. One microphone picks up what we would hear with our left ear, and another microphone picks up what we would hear with our right ear. The left (L) and right (R) signals from the microphones, or from playback equipment if the broadcast is recorded, are added together to form an L + R signal. The L + R signal is sometimes called the **MAIN CHANNEL**.

The L + R signal is only a part of the complete stereo signal that modulates the carrier of the FM transmitter. To form another part of the complete stereo signal, the R signal is subtracted from the L signal to form an L − R signal. This L − R signal is used to amplitude modulate a 38-kHz subcarrier. A **SUBCARRIER** is a carrier lower in frequency than the main carrier. A balanced modulator then processes the L − R signal and the 38-kHz subcarrier so that the subcarrier is suppressed and only the L − R sidebands are retained. The sideband frequencies produced when the L − R signal modulates the 38-kHz subcarrier occupy the frequency range from 23 to 53 kHz (38 ± 15 kHz). This band of frequencies is called the **STEREO SUBCHANNEL**. The suppression of the 38-kHz subcarrier reduces transmitter power requirements and also prevents interference at the receiver. The final, essential part of the complete stereo signal is a 19-kHz **PILOT SIGNAL**. This pilot signal is required by the stereo receiver to process the L − R signal so that it can be combined with the L + R signal for proper two-channel reception.

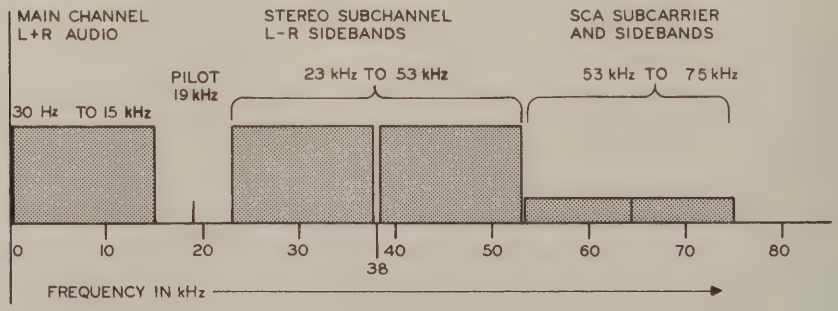


Figure 1-32

Figure 1-32 shows the arrangement of the complete stereo signal which frequency modulates the main carrier of the FM transmitter. The SCA subcarrier signal shown in Figure 1-32 is discussed in the next section of this lesson.

SCA

In addition to the stereo multiplex signal, FM broadcast stations are permitted to transmit another multiplex signal. The transmission of this multiplex signal is authorized by the FCC under the Subsidiary Communications Act (SCA).

An FM broadcast station may use the SCA signal to transmit a program consisting of special program music. Individuals or organizations then subscribe to the service for a fixed fee. The SCA signal is a subcarrier like the one used for stereo in that only special receivers can make use of this signal. The SCA signal cannot be demodulated by either monophonic or stereophonic FM receivers designed for home use. The SCA subcarrier is FREQUENCY MODULATED with the special program music.

The SCA signal, the main channel signal and the stereo subchannel signal then all frequency modulate the main carrier. Other SCA subcarrier frequencies can be used if the station is transmitting a monophonic signal. However, during stereo transmission, the SCA subcarrier and sidebands must lie between 53 kHz and 75 kHz. Figure 1-32 shows the location of the SCA subcarrier at about 67 kHz.

MODULATION INDEX, EFFECTIVE BANDWIDTH AND NUMBER OF SIGNIFICANT SIDEBAND PAIRS

The effective bandwidth of a frequency-modulated signal is determined by the number of significant sideband pairs. The number of significant sideband pairs is, in turn, determined by the modulation index. The table of Figure 1-33 gives the relationship between the modulation index, the number of significant sideband pairs and the effective bandwidth. The numbers in the third column indicate multiples of the modulating frequency.

To use the table, let's assume that a modulating signal of 4 kHz is causing a frequency deviation of 60 kHz. In this case the modulation index is:

$$\frac{60 \text{ kHz}}{4 \text{ kHz}} = 15.$$

Referring to Figure 1-33, when the modulation index is 15, we find that 19 significant sideband pairs are produced and the effective bandwidth is 38 times the modulating frequency (38 f_m). Multiplying 38 by 4 kHz gives an effective bandwidth of 152 kHz.

MODULATION INDEX	NUMBER OF SIGNIFICANT SIDEBAND PAIRS	EFFECTIVE BANDWIDTH ($\times f_m$)
0.5	2	4
1	3	6
2	4	8
3	6	12
4	7	14
5	8	16
6	9	18
7	11	22
8	12	24
9	13	26
10	14	28
11	15	30
12	16	32
13	17	34
14	18	36
15	19	38
16	20	40
17	21	42
18	23	46
19	24	48
20	25	50
21	26	52
22	27	54
23	28	56
24	29	58
25	30	60

Figure 1-33

Taking another example, let's assume that a modulating signal of 10 kHz is causing a frequency deviation of 75 kHz (100% modulation). In this example, the modulation index is:

$$\frac{75 \text{ kHz}}{10 \text{ kHz}} = 7.5$$

When the modulation index contains a fraction, and the fraction is $^1/_2$ or more, use the next higher index. If the fraction is less than $^1/_2$, use the next lower index. From Figure 1-33, using a modulation index of 8, there are 12 significant sideband pairs produced and the effective bandwidth is 24 times the modulating frequency. Multiplying 24 by 10 kHz gives an effective bandwidth of 240 kHz, which is more than the 200-kHz channel width allotted to an FM station. In actual practice, very little trouble is encountered because the higher frequency audio signals seldom have enough amplitude to cause 100% modulation.

When the modulation index is any value less than 0.5, one significant sideband pair is produced. Thus, the minimum bandwidth is equal to twice the frequency of the modulating signal.

SUMMARY

When a carrier and modulating signal are combined in a nonlinear circuit, amplitude modulation occurs. An amplitude-modulated r-f carrier consists of the carrier and two r-f sidebands. The sum of the r-f and a-f signals produces the upper sideband, and the difference between the r-f and a-f signals produces the lower sideband.

Amplitude modulation of a signal is usually expressed in terms of percentage. As the modulation percentage is increased toward 100%, more power is added to the sidebands. At 100% modulation, the modulated envelope decreases to zero and increases to twice the level of the unmodulated carrier. Also, at 100% modulation, the sideband power is increased to 50% of the carrier power. The total transmitted power is equal to the carrier power plus the sideband power. Overmodulation causes distortion of the intelligence carried. Overmodulation requires a much wider bandwidth, possibly producing interference with stations on adjacent channels.

Modulation systems can be divided into two groups: high- and low-level modulation. High-level modulation takes place in the final power amplifier plate or collector circuit of the transmitter. Low-level modulation can be accomplished in a circuit preceding this stage. Low-level modulation requires a modulating signal of less power for the same percentage of modulation than does high-level modulation.

The following Practice Exercise questions cover the subjects which you have just studied. They are:

- MODULATOR SYSTEMS
  - DIRECT FM
  - INDIRECT FM
  - REACTANCE TUBE MODULATOR
  - SERRASOID PHASE MODULATOR
- STEREOPHONIC MULTIPLEXING
- SCA
- MODULATION INDEX, EFFECTIVE BANDWIDTH AND NUMBER OF SIGNIFICANT SIDEBAND PAIRS

53. The modulation occurs in the master oscillator in the (a) direct FM system, (b) indirect FM system.

54. For linear operation of an FM modulator system, what should be the frequency deviation caused by a 2-volt modulating signal if a 1-volt modulating signal causes a frequency deviation of ±3.5 kHz?

55. What are the two major problems of the simple direct FM system of Figure 1-24?

56. To what frequency is the output circuit of a frequency doubler tuned?

57. Assume that a 1.8-MHz oscillator is being deviated ±1 kHz and its output is fed to one doubler and three triplers. What is the carrier center frequency, and what is the carrier deviation?

58. The AFC circuit in Figure 1-26 controls the percent of modulation. True or False?

59. In an indirect FM system, the frequency of the master oscillator remains constant. True or False?

60. When an r-f signal is phase modulated, the desired frequency deviation should be (a) independent of the modulating signal frequency, (b) proportional to the modulating signal frequency.

61. What is the function of the audio corrector in an indirect FM system using phase modulation?

62. Basically, what components determine the frequency of oscillation in the V_1 circuit of Figure 1-29?

63. In Figure 1-29, V_1 acts as a variable (a) inductance, (b) capacitance.

64. What is the phase relationship between the V_1 plate voltage and plate current in Figure 1-29?

65. When the audio modulating signal causes the V_1 screen voltage in Figure 1-29 to become more positive, the frequency of V_2 oscillation increases. True or False?

66. What is the advantage of an indirect FM system compared to a direct FM system?

67. Why is such a large frequency multiplication required in the serrasoid phase modulator of Figure 1-30?

68. To produce a stereo effect, the number of separate sound signals needed is (a) one, (b) two.

69. What is a subcarrier?

70. The left (L) and right (R) audio signals are added together to form an L + R signal in the FM stereo multiplex system. This signal frequency modulates the main carrier. How is the L − R signal transmitted?

71. What is the function of the 19-kHz pilot signal in the FM stereo multiplex signal?

72. The SCA subcarrier frequency in Figure 1-32 is (a) 19 kHz, (b) 38 kHz, (c) 67 kHz.

Frequency modulation is another method of modulating an r-f carrier. In FM, the frequency of the r-f carrier is varied by a low-frequency modulating signal. The amount of carrier deviation is proportional to the amplitude of the modulating signal. The rate of carrier deviation is proportional to the frequency of the modulating signal.

Both the amount of carrier deviation and the rate of carrier deviation are limited by the FCC. In the FM broadcast band (88–108 MHz), the amount of carrier deviation is limited to 75 kHz above and below the carrier center frequency. Thus, there is a total swing of 150 kHz. This is considered 100% modulation. In TV broadcasting, the amount of frequency deviation of the sound carrier is limited to 25 kHz above and below its center frequency. In TV this is considered 100% modulation. Thus, for any FM transmission, 100% modulation is the maximum amount of carrier frequency deviation authorized by the FCC.

When an r-f carrier is frequency modulated, power is transferred from the carrier to the sidebands. Thus, in an FM transmission, the total amount of power being radiated is constant, regardless of the percentage of modulation.

In some transmitters, modulation is accomplished by causing the audio signal (or any modulating signal) to vary the frequency of the master oscillator directly. An indirect method of modulation is employed in other FM transmitters. Here, the audio signal is made to change the phase of the r-f signal in a stage following the oscillator. This effectively produces frequency modulation.

PART 2—DEMODULATION AND DETECTION

In a transmitter, the information (voice, music, picture, etc.) to be transmitted is impressed on a carrier wave. The process of impressing information on a carrier wave is called modulation. In the modulation process, some characteristic of the carrier wave such as frequency or amplitude is varied by the modulating signal.

In frequency modulation (FM), the frequency of the carrier swings above and below a center frequency. The amplitude of the modulating signal determines the amount of swing. The frequency of the modulating signal determines the rate at which the carrier frequency varies.

In amplitude modulation (AM), the amplitude of the carrier varies with the modulating signal. The amplitude of the modulating signal determines the maximum and minimum amplitudes of the modulated carrier. The frequency of the modulating signal determines the frequency at which the amplitude of the carrier varies.

In both AM and FM the modulation process produces new bands of frequencies above and below the original carrier frequency. These new bands of frequencies are called the upper and lower sidebands, respectively. For example, assume that a carrier is amplitude modulated by a single sinusoidal modulating frequency. The upper sideband frequency is equal to the sum of the carrier frequency and the modulating frequency. The lower sideband frequency is equal to the difference between the carrier frequency and the modulating frequency.

In one variation of AM called single sideband (SSB), only one sideband is transmitted. The other sideband and the carrier are both suppressed at the transmitter. In this case, the carrier frequency must be reinserted at the receiver.

The end purpose of the modulating signal is to actuate a transducer, such as a speaker or picture tube, at the receiver. Although the transmitted signal contains the desired information, it is not capable of actuating a transducer directly. In order for the modulating signal to actuate a transducer, it must be recovered from the transmitted signal. The process of recovering the modulating signal from the transmitted signal is the reverse of the modulation process. It is called **DEMODULATION**. Sometimes this process is also called **DETECTION**. The circuits used for this process are called **DEMODULATORS** or **DETECTORS**.

A different type of demodulator is required for each type of modulation. Frequency modulation requires an FM demodulator, and amplitude modulation requires an AM demodulator. SSB transmission requires a special type of AM demodulator which has some provision for reinserting the carrier frequency. In this case, the carrier frequency is produced by an oscillator in the receiver.

AM DETECTION

Amplitude modulation is used in the standard broadcast band (535 kHz to 1605 kHz). Amplitude modulation is also used for two-way communications, amateur communications, citizens band communications, telemetry and many other applications.

The diode is the most popular device used for AM detection. This type of detector is found in almost all standard AM broadcast receivers. Figure 2-1

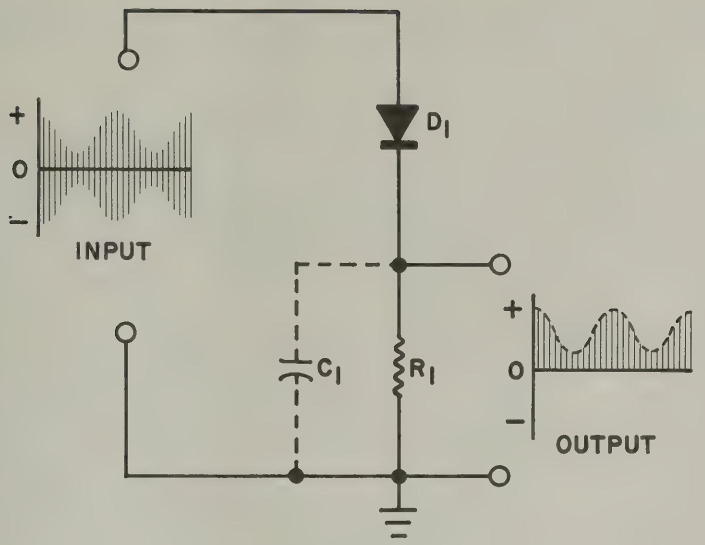


Figure 2-1

shows how a diode is used to recover the modulating signal from an amplitude-modulated carrier. The amplitude-modulated carrier is applied to the input terminals. Remember that a diode conducts only in one direction. Thus, current exists only in one direction in the circuit and, disregarding C_1, only the positive alternations of the input signal are developed across load resistor R_1.

These high-frequency positive alternations of the input signal cannot directly actuate a transducer to reproduce the original information. The modulating signal has not been completely recovered. To complete the job, capacitor C_1 is connected across R_1. The capacitor smooths out the high-frequency pulses and produces an output that is proportional to the changes in amplitude of the pulses.

The voltage developed by a diode detector varies at the same rate as the original modulating signal. This is shown by the dashed line output curve in Figure 2-1. To obtain this output, the complete diode detector circuit acts as both a rectifier and a filter.

Notice that the waveform of the varying dc of Figure 2-1 is determined by the changes in amplitude of the incoming AM carrier. The importance of this will be explained later in this lesson. Also notice that if the diode were reversed, only the negative pulses of the incoming carrier would be developed across R_1. The output of Figure 2-1 would then be inverted. This is important because receivers are designed to detect only one polarity of the input signal. Technicians sometimes make the mistake of installing semiconductor diodes backwards in receivers. This results in faulty receiver operation.

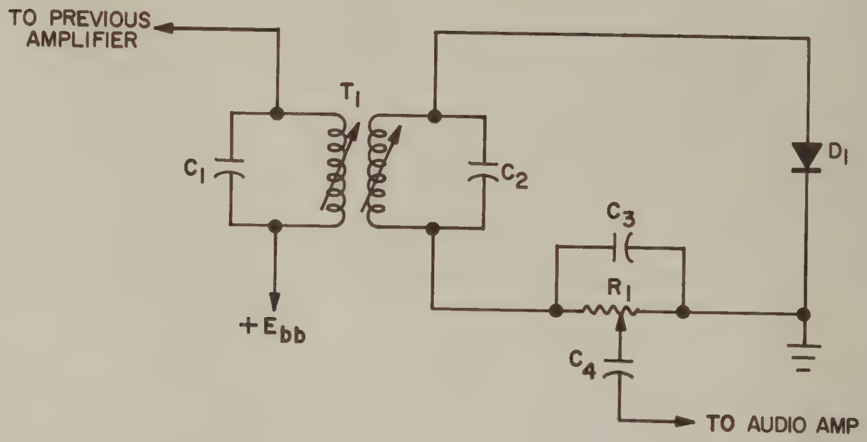


Figure 2-2

Figure 2-2 shows a more practical arrangement of a diode detector circuit, as it appears in an actual receiver. Before being applied to the detector, the incoming AM carrier may pass through several amplifiers. The modulated AM carrier is coupled from an amplifier to the detector by the double tuned transformer, T_1. Diode D_1, resistor R_1 and capacitor C_3 of Figure 2-2 correspond to diode D_1, resistor R_1 and capacitor C_1 of Figure 2-1. In Figure 2-2 the load resistor, R_1, is a potentiometer. In a radio receiver, the potentiometer serves as the volume control. The output voltage can be varied according to the setting of R_1. Coupling capacitor C_4 only passes the variations of voltage, called the ac components, to the input of the audio amplifier.

AM Receivers

If the AM detector of Figure 2-1 were preceded by a tuned circuit and an antenna and followed by a pair of headphones, it would make up a complete AM radio receiver. In fact, some of the earliest radio receivers were made in this way. This type of receiver is called a **TUNED RADIO-FREQUENCY (TRF) RECEIVER**. One way to improve the performance of the receiver is to add one or more tuned r-f amplifiers between the antenna and the detector. The output of the detector may then be fed through an audio amplifier to a speaker, rather than directly to a pair of headphones.

One major disadvantage of the TRF receiver is that many tuned circuits have to be adjusted at the same time to select the desired frequency. Thus, the large number of tuning controls on a TRF receiver makes tuning difficult and time-consuming.

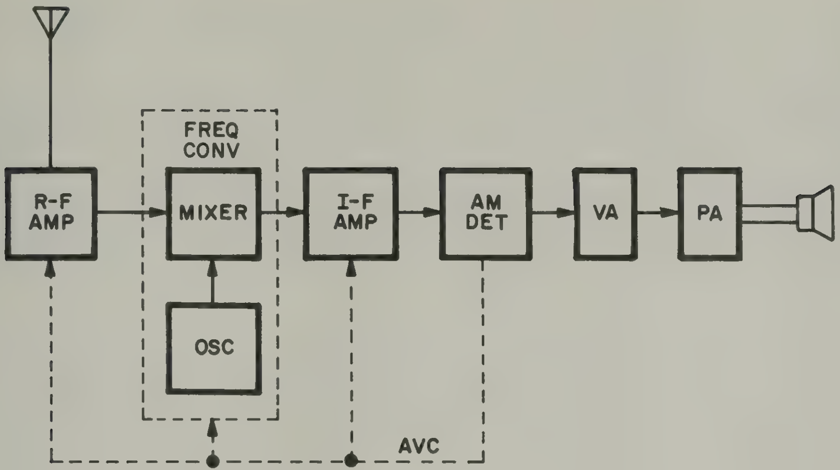


Figure 2-3

Figure 2-3 is a block diagram of another type of receiver which requires a simpler tuning system. This type of receiver is called a **SUPERHETERODYNE RECEIVER**. Almost all broadcast receivers in use today are of this type. An r-f amplifier is NOT always used in a superheterodyne receiver. A superheterodyne receiver converts any incoming r-f carrier to an **INTERMEDIATE FREQUENCY**. Regardless of the frequency of the r-f carrier, the intermediate frequency is always the same. The most common intermediate frequency used in home-entertainment AM broadcast band receivers is 455 kHz.

The tuned amplifiers used to amplify the intermediate frequency are appropriately called i-f amplifiers. The use of a constant intermediate frequency eliminates the need to retune the i-f amplifiers each time the receiver is tuned to a different r-f carrier frequency. The i-f amplifiers of a superheterodyne receiver are tuned at the factory, and normally it is not necessary to retune them.

The r-f amplifier between the antenna and the frequency converter in Figure 2-3 is optional in an AM broadcast receiver. Many receivers operate very well without one.

The Frequency Converter

The frequency converter changes the desired incoming r-f carrier frequency to the intermediate frequency. As shown in Figure 2-3, the frequency converter is made up of a special type of r-f circuit called a **MIXER** and an r-f oscillator called a **LOCAL OSCILLATOR**. Both the incoming carrier and the output of the local oscillator are applied to the mixer. In the mixer, the incoming carrier frequency beats against, or heterodynes with, the local oscillator frequency. Thus, the mixer output contains frequencies equal to: (1) the original incoming carrier and sideband frequencies, (2) the local oscillator frequency, and (3) the sum and difference frequencies obtained from mixing the local oscillator frequency and the incoming carrier and sideband frequencies. The i-f amplifiers of this receiver are tuned to the difference frequencies. These, then, are the only frequencies that are passed to the detector.

In most AM broadcast receivers, the local oscillator is tuned to a frequency 455 kHz above the incoming carrier frequency. The variable capacitor used to tune the oscillator is mechanically coupled to, or ganged with, the variable capacitor used to tune the r-f input circuit. Thus, when you change the setting of the r-f input tuning capacitor, you automatically change the setting of the oscillator tuning capacitor so that the difference frequency is always 455 kHz.

As an example of mixer action, assume that the incoming carrier frequency is 1000 kHz and the local oscillator frequency is 1455 kHz. Disregarding the sidebands for the moment, the frequencies at the output of the mixer are 1000 kHz, 1455 kHz, 2455 kHz and 455 kHz. These are the two original frequencies applied to the mixer and both the sum and difference frequencies. The tuned circuits which follow the mixer, however, are tuned to pass only signals with frequencies near 455 kHz. As a result, the other frequencies developed by the mixer do not appear at later points in the receiver. Only the 455-kHz carrier and its sidebands are passed and used.

The I-F Amplifier

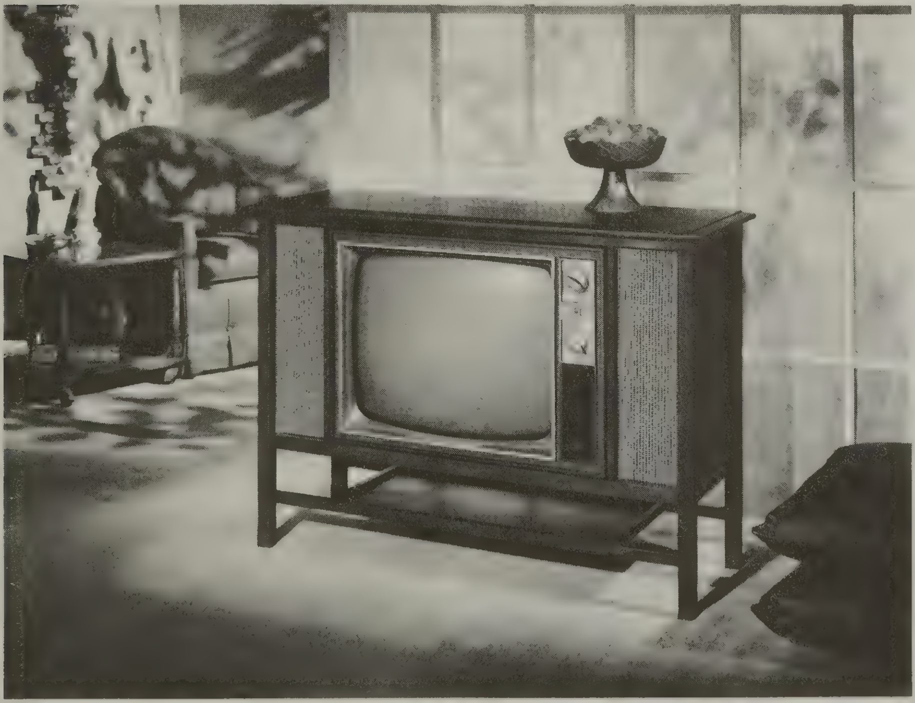
The intermediate-frequency signal carrier has both upper and lower i-f sidebands. In AM, the upper sideband frequencies are equal to the sums of the i-f carrier and the modulating frequencies. The lower sideband frequencies are equal to the differences between the i-f carrier and the modulating frequencies. This is similar to the relationship between the frequencies of the sidebands and the carrier produced at the transmitter. The difference is that the carrier frequency has now been converted to the intermediate frequency.

A maximum audio frequency of about 5 kHz will produce satisfactory listening for most purposes. Therefore, the bandwidth of the i-f amplifiers in most standard AM broadcast radios is about 10 kHz. This allows the i-f amplifiers to pass sideband frequencies 5 kHz above and below the 455-kHz carrier. High-fidelity AM receivers, of course, may have a somewhat wider bandwidth to reproduce an even wider range of audio frequencies.

Automatic Volume Control

Most AM broadcast receivers contain an **AUTOMATIC VOLUME CONTROL (AVC)** system. The automatic volume control system reduces excessive changes in volume due to changes in the strength of the incoming signal. The signal strength at the antenna, for example, is normally much greater for powerful or nearby stations than it is for weaker or more distant stations. Without AVC, the sound from the receiver speaker would be much louder for the more powerful or nearby stations than it would be for weaker or more distant stations. AVC also helps to reduce fading of the sound in automobile receivers due to changes in physical surroundings such as when traveling past a tall building or under a viaduct or overpass.

As previously mentioned, the detector output is proportional to the strength of the incoming signal. The output is a dc voltage which varies in proportion to the modulating signal. With AVC, a part of this varying dc voltage is filtered to remove the audio variations. It is then used as the bias voltage for the preceding i-f or r-f stages. This bias voltage changes the operating points of the tubes or transistors in the amplifier stages. The gain of these stages varies with changes in operating point caused by bias changes.



Diode detectors are used to recover the picture information from a transmitted television signal. The picture or video section of a TV receiver is essentially an AM superheterodyne receiver.

Courtesy Motorola, Inc.

Thus, the bias voltage obtained from the detector output controls the gains of the amplifiers. This action tends to keep the average level of the detector output relatively constant, regardless of the strength of incoming signal.

An AM Radio Schematic

Figure 2-4 is the schematic diagram of the tuning circuit and detector of an AM radio receiver. The Q_1 stage is the frequency converter, the Q_2 and Q_3 stages are i-f amplifiers, and the D_1 circuit is the detector. The output of the detector is amplified by the audio amplifier and applied to the speaker.

The Q_1 frequency converter stage is called an **AUTODYNE CONVERTER**. The same transistor performs both the mixer and local oscillator functions. In the oscillator portion of the circuit, the secondary of T_2 is tuned to the desired frequency by capacitors C_3 and C_4. Capacitor C_6 and resistor R_3 couple the secondary oscillator voltage to the emitter of Q_1. This voltage is amplified by the transistor. The T_2 primary (also called a feedback or tickler winding) in the collector circuit of Q_1 provides a positive (regenerative) feedback voltage of the proper magnitude to sustain oscillations.

Notice that one end of the emitter circuit of Q_1 is connected to a tap on the T_2 secondary. This causes the T_2 secondary to act like an autotransformer, providing the proper impedance match between the high impedance tank circuit and the relatively low impedance of the emitter circuit.

In the mixer portion of the circuit, loopstick antenna T_1 is tuned to the desired carrier frequency by capacitors C_1 and C_2. The loopstick antenna is a type of built-in antenna made up of coils wound on a ferrite core. Transistor Q_1 is biased by the R_1R_2 voltage divider so that it operates along a nonlinear portion of its characteristic curve. This causes the incoming modulated carrier to mix with the output of the local oscillator. Thus, the Q_1 collector circuit contains the original frequencies and the sum and difference frequencies.

Capacitors C_2 and C_4 make up a two-gang variable capacitor. The two capacitors are ganged together so that as the radio is tuned to a different carrier, the frequency of the local oscillator remains 455 kHz above the carrier. Capacitors C_1 and C_3 are trimmer capacitors connected across the tuning capacitors. These trimmer capacitors are adjusted so that C_2 will tune through the desired range (the standard AM broadcast band, 535 kHz-1605 kHz), while the local oscillator frequency remains exactly 455 kHz above the incoming carrier. The primary of T_3 and C_8 form a tank circuit in the collector circuit of Q_1. The tank circuit is tuned to the intermediate

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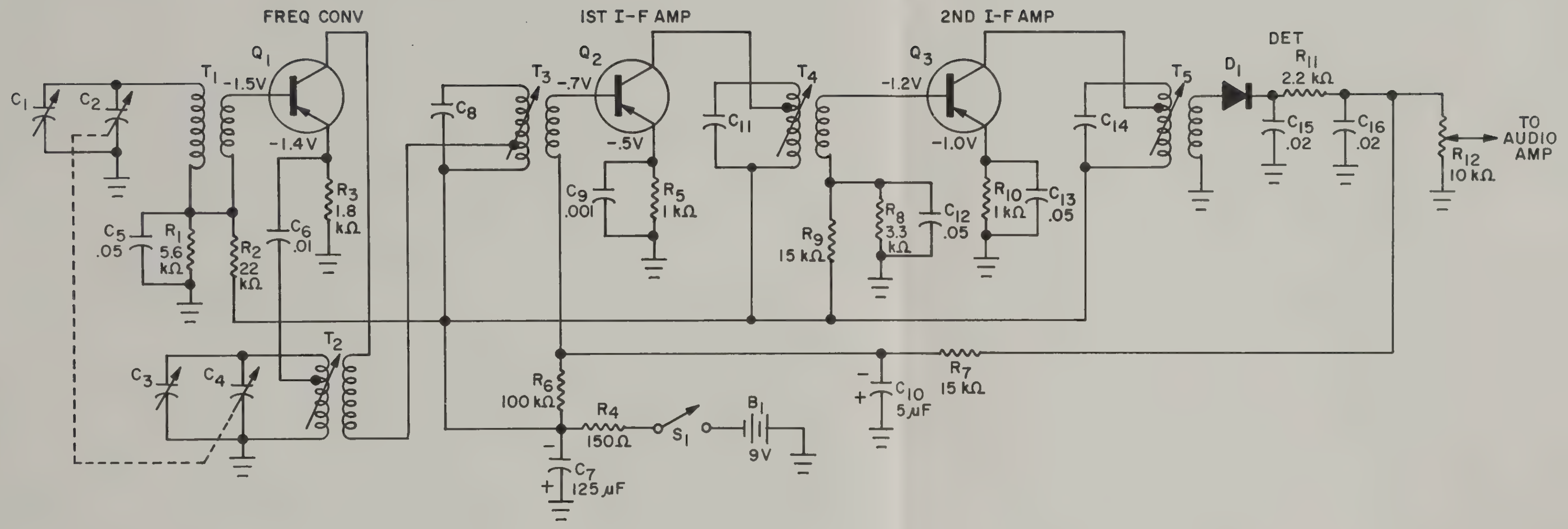

FREQ CONV
IST I-F AMP
2ND I-F AMP
DET
Q_1
T_1
-1.5V
-1.4V
C_1
C_2
R_3 1.8 kΩ
C_5 .05
R_1 5.6 kΩ
R_2 22 kΩ
C_6 .01
T_2
C_3
C_4
C_8
T_3
Q_2
-.7V
-.5V
C_9 .001
R_5 1 kΩ
C_{11}
T_4
Q_3
-1.2V
-1.0V
R_9 15 kΩ
R_8 3.3 kΩ
C_{12} .05
R_{10} 1 kΩ
C_{13} .05
C_{14}
T_5
D_1
R_{11} 2.2 kΩ
C_{15} .02
C_{16} .02
R_{12} 10 kΩ
TO AUDIO AMP
R_6 100 kΩ
R_4 150Ω
S_1
B_1
9V
C_7 125 μF
C_{10} 5 μF
R_7 15 kΩ

Figure 2-4

87. In Figure 2-3, what type of signal is normally present at the input to the AM detector?

88. In Figure 2-3, what type of signal is normally present at the output of the AM detector?

89. The i-f bandwidth of most standard AM broadcast radios is about (a) 5 kHz, (b) 10 kHz, (c) 20 kHz.

90. AVC voltage is (a) ac, (b) dc.

91. The AVC voltage in a standard AM broadcast receiver is usually obtained from the (a) frequency converter, (b) detector, (c) power amplifier.

This communications receiver contains separate product and AM (diode) detectors for SSB and AM reception.
Courtesy Hammarlund Mfg. Co.

frequency (455 kHz) by adjusting the T_3 primary. Thus, only the difference frequencies at the output of the converter are applied to the i-f amplifiers. Similarly, the tank circuits of T_4 primary and C_{11} and T_5 primary and C_{14} are tuned to 455 kHz to provide greater selectivity. The process of adjusting the trimmer capacitors and the i-f transformers so that the respective tank circuits are tuned to the correct frequencies is called **ALIGNMENT**.

The primaries of T_3, T_4 and T_5 are tapped to provide the proper impedance match between the respective collectors and the tuned circuits. Base bias for Q_2 is obtained from the AVC circuit, which will be explained later, and base bias for Q_3 is obtained from the R_8R_9 voltage divider. Resistors R_5 and R_{10} and bypass capacitors C_9 and C_{13} provide dc stabilization for Q_2 and Q_3.

The detector circuit consists of D_1, the secondary of T_5, low-pass filter C_{15}, R_{11} and C_{16}, and volume control R_{12}. The detected or demodulated signal is coupled from the movable contact of R_{12} to an audio amplifier. Also, the demodulated signal at the junction R_{11}, C_{16} and R_{12} is fed through a filter network to provide an AVC voltage for the first i-f amplifier, Q_2.

The base circuit of Q_2 is connected to the junction of R_6 and R_7. Resistors R_6 and R_7 act as a voltage divider between the collector supply terminal and the ungrounded side of R_{12}. The voltage at the junction of R_6 and R_7 varies in step with the dc component across R_{12}, and thus serves as an AVC voltage. Resistor R_7 and capacitor C_{10} make up an AVC filter to smooth out audio variations in the AVC voltage.

SINGLE SIDEBAND DETECTION

As mentioned previously, only one sideband is transmitted in single sideband transmission. Single sideband transmission is often used in amateur radio communications and some other two-way communications. At present, however, it is not used in commercial AM broadcasting.

Unless a carrier is applied to the detector, together with the sidebands, the detector output is not intelligible. Remember, the modulating signal frequency is the difference between the carrier and the sideband frequencies. Therefore, a carrier must be present at the detector.

In an ordinary AM signal, the carrier and both sidebands are present. In an AM detector, the sidebands beat against, or heterodyne with, the carrier in the detector. The difference frequencies obtained in this process represent the modulating signal.

In single sideband reception, a carrier must be inserted. A carrier signal is provided by an oscillator built into the receiver. This oscillator is called a beat frequency oscillator (BFO). To detect a single sideband signal, the frequency of the BFO must be within 10 Hz of the carrier frequency if the output of the detector is to sound normal. The BFO must therefore be adjusted periodically to insure that it does not drift far from the carrier frequency.

The carrier must be inserted before detection takes place. The amplitude of the combined wave varies in accordance with the original modulation. The detector is often a simple diode detector, which detects the composite signal in the same manner as it would an AM signal.

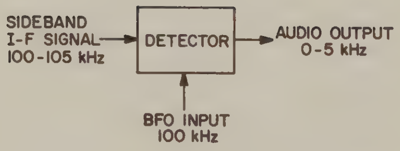


Figure 2-5

Notice in Figure 2-5 that the sideband signal applied to the detector has been converted to an i-f signal which is within a frequency range of 100 to 105 kHz. If the BFO provides a frequency of exactly 100 kHz, the two signals combine to produce a difference frequency that is between 0 and 5 kHz. It is this difference frequency that is detected and sent on to the audio stages of the receiver. Heterodyning as well as detection are the actions that occur.

Since no carrier power is present in single sideband transmission, reliable reception at much greater distances is possible with single sideband as compared to ordinary AM transmission with equal amounts of radiated power. Note also that because only one sideband is present in SSB transmission, the i-f bandwidth of an SSB receiver is only about half that of a conventional AM communications receiver.

FM DETECTION

The basic difference between an AM superheterodyne receiver and an FM superheterodyne receiver is the type of detector or demodulator. In an AM receiver, the detector must respond to changes in amplitude of the modulated signal. In an FM receiver, the detector must respond to changes in frequency of the modulated signal.

Other differences between FM and AM broadcast receivers are mostly due to the different frequencies of the FM and AM bands. The AM broadcast band extends from 535 kHz to 1605 kHz, while the FM broadcast band extends from 88 MHz to 108 MHz. Standard AM broadcast receivers usually have intermediate frequencies of about 455 kHz, and FM broadcast receivers usually have intermediate frequencies of about 10.7 MHz.

Also, as previously explained, the standard AM broadcast receiver has a bandwidth of about 10 kHz. In FM broadcasting however, the carrier swings 75 kHz above and below the center or resting frequency at 100% modulation. But more significant than this, an FM signal contains sideband pairs extending above and below the maximum and minimum frequency swings of the carrier. To provide high-fidelity reception, the i-f bandwidth of a standard FM broadcast receiver may be between 150 kHz and 300 kHz.

Because an FM broadcast receiver operates at higher frequencies, the wiring and parts layout of an FM receiver is more critical than those of an AM broadcast receiver. At the higher carrier and intermediate frequencies used in FM broadcasting, lead (wiring) inductance and capacitance play an important part in circuit operation.

This FM stereo receiver uses a Foster-Seeley discriminator. The output of the discriminator is applied through a stereo demultiplexer to a 70-watt stereo amplifier.
Courtesy H. H. Scott, Inc.

The Foster-Seeley Discriminator

Figure 2-6 is the schematic diagram of a common FM detector called a **FOSTER-SEELEY DISCRIMINATOR**. This discriminator has two similar diodes, D_1 and D_2. These may be either semiconductor diodes, as in Figure 2-6, or vacuum tube diodes. Diode load resistors R_1 and R_2 are equal, as are capacitors C_4 and C_5.

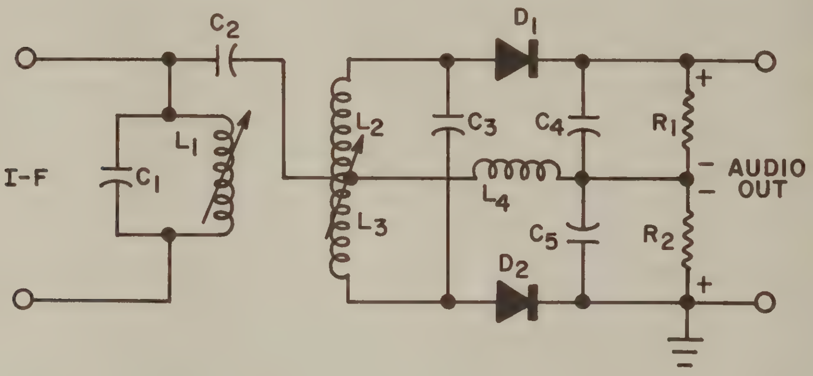


Figure 2-6

The primary (L_1) and secondary windings (L_2 and L_3) of the discriminator transformer are tuned to resonance at the center frequency of the i-f signal, usually 10.7 MHz in an FM broadcast receiver. In addition to the transformer coupling, the primary voltage is coupled to the center tap of the secondary by capacitor C_2. This voltage appears across radio-frequency choke L_4.

The Foster-Seeley discriminator is made up of two separate rectifier circuits. One circuit is made up of L_2, L_4, C_4, R_1 and D_1. The other circuit is made up of L_3, L_4, C_5, R_2 and D_2. Notice that L_4 is common to both circuits. Capacitor C_3 tunes the transformer secondary, made up of L_2 and L_3, to the center frequency of the i-f signal.

The diodes are connected so that the direction of current through R_1 is opposite that through R_2. Thus, the polarity of the voltage across R_1 is opposite that across R_2, as indicated in Figure 2-6. The output voltage is equal to the difference between the voltages across the two resistors.

The voltages across L_2 and L_4 act as the source for the D_1 circuit, and the voltages across L_3 and L_4 act as the source for the D_2 circuit. At resonance, the phase relationship between the voltages across L_2 and L_4 is the same as the phase relationship between the voltages across L_3 and L_4. Equal voltages are applied to the D_1 circuit and the D_2 circuit. The voltages developed across R_1 and R_2 are equal but opposite in phase. These voltages cancel and the output is zero.

The voltages at the upper and lower ends of the transformer secondary, across windings L_2 and L_3, are always 180° out-of-phase with respect to the center tap. At frequencies off resonance, the tank circuit made up of L_2, L_3 and C_3 is either inductive or capacitive. This causes the phase angle between the transformer secondary voltage and the voltage across L_4 to vary with frequency. Above resonance, the phase angle between the L_3 and L_4 voltages is less than the phase angle between the L_2 and L_4 voltages. The vector sum of the L_3 and L_4 voltages is greater than the vector sum of the L_2 and L_4 voltages. The voltage across R_2 is greater than that across R_1, and the output is negative.

This r-f signal generator is designed for troubleshooting and alignment of FM and AM receivers.
Courtesy RCA-Electronic Components Division

Below resonance, the phase relationships reverse and the output is positive. Thus, the output voltage varies above and below the center frequency. The variations in output voltage are an exact reproduction of the original modulating signal.

A discriminator circuit like Figure 2-6, or a variation of it, is used for a variety of applications in electronic equipment. In fact, wherever it is necessary to convert changes of frequency into changes of amplitude, a discriminator circuit is used. Because it is such a widely used circuit, let's take the time to analyze the discriminator circuit of Figure 2-6 in greater detail by means of the vector diagrams of Figure 2-7.

As shown in Figure 2-7A, the voltage across tuned primary L_1 is represented by vector E_{L_1}. Since the L_1 reactance is much greater than its resistance, the primary current, represented by vector I_{L_1}, lags voltage E_{L_1} by approximately 90°. The magnetic field set up around primary winding L_1 varies with the current; therefore, vector I_{L_1} also represents the magnetic flux. These flux lines extend through the secondary windings L_2L_3 and induce a voltage, E_I. The amplitude of E_I is proportional to the rate of cutting. Because the rate of cutting is greatest when the primary current, I_{L_1}, is passing through zero, and lowest when I_{L_1} is maximum, induced voltage E_I lags the flux and I_{L_1} by 90°. Therefore, Figure 2-7A shows induced voltage E_I in the transformer secondary, lagging I_{L_1} by 90°, or 180° out-of-phase with E_{L_1}.

At the resonant frequency of tuned circuit $L_2L_3C_3$, the inductive and capacitive reactances are equal and the circuit is purely resistive. As shown in Figure 2-7B, secondary current I_S is in phase with E_I under these conditions.

Since the voltage across an inductor leads the current through it by 90°, the voltage across secondary windings L_2L_3 leads I_S by 90°. However, with the center tap serving as the reference point, voltage E_{L_2} is 180° out-of-phase with voltage E_{L_3}. The phase relationships of I_S, E_{L_2} and E_{L_3} are shown by the vectors of Figure 2-7B.

As shown in the circuit of Figure 2-6, the signal voltage, E_{L_1}, is coupled through capacitor C_2 and developed across choke L_4. The reactance of choke L_4 is very high compared to that of coil L_1, and the choke has little effect upon the total impedance of the tuned primary circuit. Therefore, voltage E_{L_4} across choke L_4 is equal to and in phase with primary voltage E_{L_1}. As shown in Figure 2-7C, E_{L_4} can be substituted for E_{L_1}.

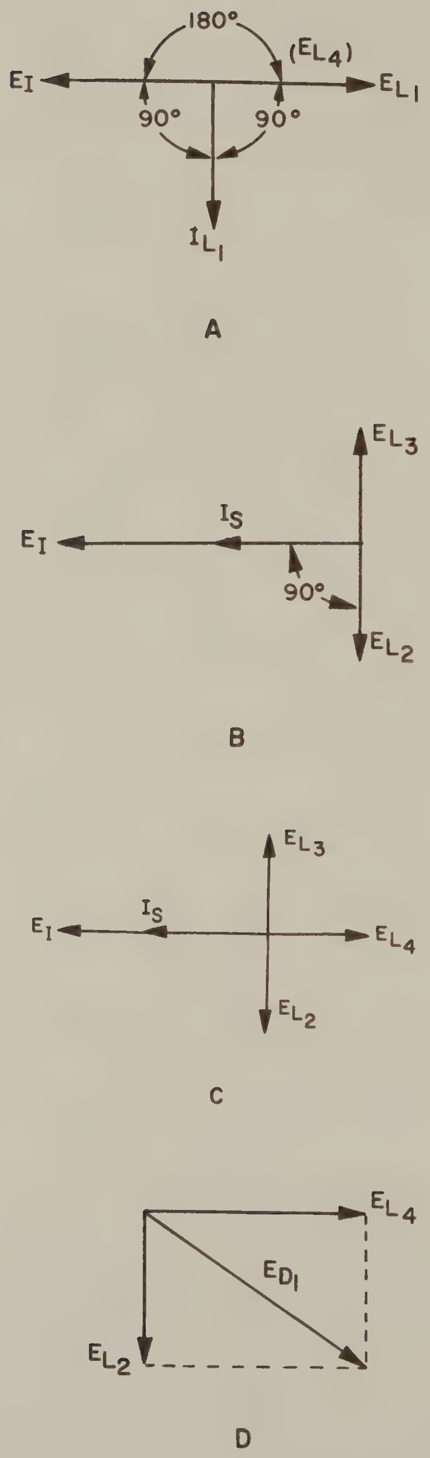


Figure 2-7

Since E_{L_2} and E_{L_4} both affect the conduction of D_1, the D_1 voltage, E_{D_1}, is the vector sum of the two voltages, E_{L_2} and E_{L_4}. At resonance, E_{L_2} and E_{L_4} are phase separated by 90°, as in Figure 2-7C, and the resultant voltage is represented by the vector, E_{D_1}, in Figure 2-7D.

Similarly, the D_2 diode circuit contains two voltages, E_{L_4} and E_{L_3}, the vector sum of which causes the D_2 current. At the resonant frequency, E_{L_4} and E_{L_3} are phase separated by 90°, and their resultant voltage is represented by vector E_{D_2} in Figure 2-7E.

The magnitudes of the diode currents depend on the amplitudes of voltages E_{D_1} and E_{D_2}. As indicated in Figures 2-7D and 2-7E, these voltages are equal at the resonant frequency, diodes D_1 and D_2 conduct equally, and equal voltages are developed across load resistors R_1 and R_2. However, because the voltages are of opposite polarity, as shown in Figure 2-6, the output voltage is zero. Thus, with both the primary and secondary circuits tuned to resonance, the discriminator output voltage is zero at the carrier frequency.

At frequencies above resonance, inductive reactance increases while capacitive reactance decreases. Therefore, the $L_2L_3C_3$ circuit becomes inductive, and current I_S lags voltage E_I by some angle, θ, as shown in Figure 2-7F. Since the voltage across secondary windings L_2L_3 is always 90° out-of-phase with current I_S, voltages E_{L_2} and E_{L_3} are shifted in phase with respect to voltage E_{L_4}.

From the plan of Figures 2-7D and 2-7E, adding the voltages vectorially, as shown in Figure 2-7G, yields resultant voltage E_{D_2}, which is greater in magnitude than resultant voltage E_{D_1}. Because of this difference in magnitude, the D_2 diode current is greater than the D_1 diode current, and the voltage across R_2 becomes greater than the voltage across R_1. Because these voltages are of opposite polarity, the output voltage is equal to the difference between them. Therefore, when the incoming signal voltage swings above resonance, voltage E_{R_2} is greater than voltage E_{R_1}, and the output voltage swings negative with respect to ground.

At frequencies below resonance, the inductive reactance decreases while the capacitive reactance increases, the circuit becomes capacitive, and I_S leads E_I, as indicated in Figure 2-7H. Voltages E_{L_2} and E_{L_3} also are shifted with respect to E_{L_4} to remain 90° out-of-phase with I_S. Under these conditions, the vector sum of voltages E_{L_2}, E_{L_3} and E_{L_4} causes the E_{D_1} voltage to be greater in magnitude than the E_{D_2} voltage, as shown in Figure

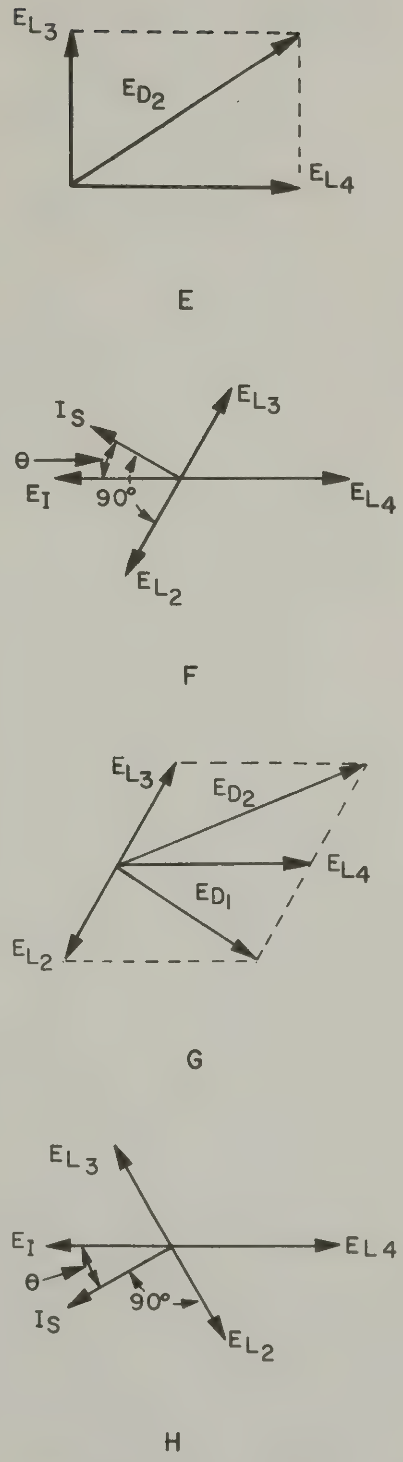


Figure 2-7

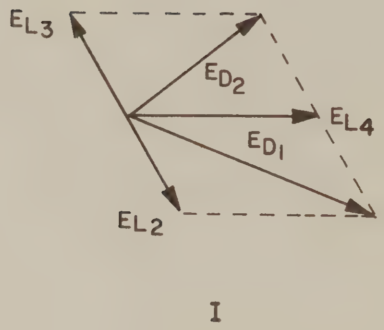


Figure 2-7

2-7I. This causes the D_1 current to be greater than the D_2 current and the voltage across R_1 is greater than the voltage across R_2. Therefore, when the incoming signal swings below resonance, the output voltage swings positive with respect to ground.

To review the action of the discriminator circuit, the voltages across load resistors R_1 and R_2 are of opposite polarity and are proportional to their respective diode currents. Therefore, the output voltage is: (1) zero when the r-f input is at the center frequency, (2) positive with respect to ground when the r-f input swings below the center frequency, and (3) negative with respect to ground when the r-f input swings above the center frequency.

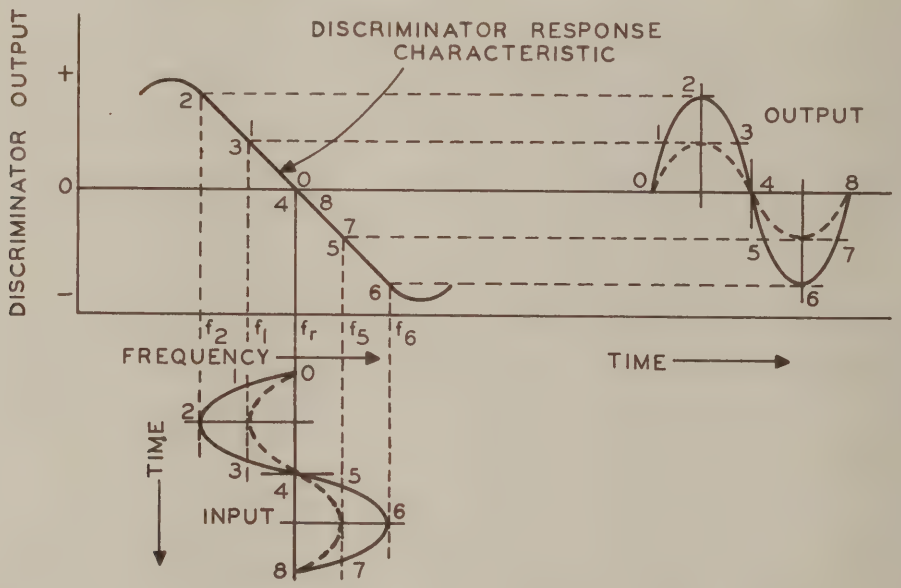


Figure 2-8

The overall response characteristic at the FM discriminator is shown by the S-shaped response curve of Figure 2-8. This curve shows the relationship between the variations of input frequency and the resulting variations of output voltage. S curves similar to Figure 2-8 can be displayed on an oscilloscope during adjustment (alignment) of FM discriminators. The spacing between the two knees of this curve should be greater than twice the frequency deviation of the FM wave at 100% modulation. The knees should appear at frequencies equally spaced above and below the i-f carrier frequency, f_r. In FM broadcast receivers, each knee is about 100 kHz from the carrier frequency.

The solid curve below the S curve of Figure 2-8 represents a swing in frequency of the frequency-modulated i-f carrier from frequency f_2 to frequency f_6. During each complete cycle of modulation, the i-f carrier frequency swings from f_r down through f_1 to f_2, then up through f_1 to f_r, and f_5 to f_6, and finally back down through f_5 to f_r. The corresponding output voltages are indicated on the S curve by the intersections numbered 0 through 8. The output voltage waveform is plotted to the right of the S curve. Thus, each complete sinusoidal swing of i-f input frequency provides one complete sinusoidal cycle of output voltage.

Since the S curve is linear over the entire swing of input frequencies, the amplitude of the output voltage is proportional to the frequency swing. Therefore, if the frequency swing is reduced, the amplitude of the output is reduced, as shown by the dashed-line input and output curves of Figure 2-8.

One disadvantage of the Foster-Seeley discriminator is not shown in Figure 2-8. The amplitude of the output voltage depends not only on the frequency swing, but also on the amplitude of the i-f signal. Thus, any amplitude modulation, such as noise or fading, present on the incoming r-f wave can be detected in the output. To prevent amplitude variation from producing an undesirable output, the Foster-Seeley discriminator is normally preceded by a special type of i-f amplifier, called a **LIMITER**, which removes any amplitude modulation of the incoming carrier.

For vacuum tube receivers, a sharp cutoff pentode may be used in the limiter stage. The tube is operated with grid leak bias, low plate and screen grid voltages—about 50 volts. Under these conditions, it saturates and cuts off at relatively low levels of input signal. As a result, the output to the discriminator does not exceed a certain level or amplitude. This limiting level is exceeded whenever a station of normal strength is received. Thus, all stations of normal signal strength cause the same amplitude of signal to reach the discriminator. Stations with less-than-normal signal strength, static and other disturbances are effectively eliminated by this limiting action.

The Ratio Detector

The **RATIO DETECTOR** is a type of FM demodulator which provides its own limiting. Figure 2-9 is the schematic diagram of a ratio detector.

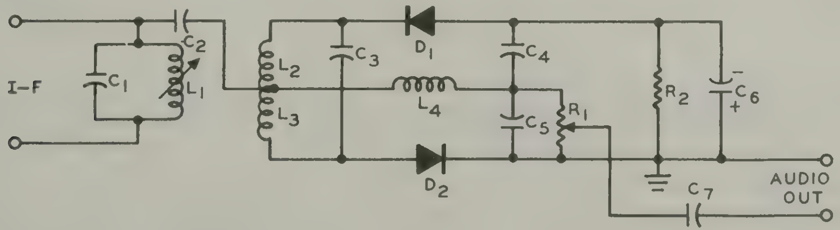


Figure 2-9

Although the diagram looks something like that of a discriminator, you can easily identify the ratio detector. The diodes of the ratio detector are connected series-aiding instead of series-opposing across the transformer secondary. The ratio detector also has electrolytic capacitor C_6 connected in series with the diodes. It is this capacitor that provides the limiting action of the ratio detector.

Capacitor C_2 is sometimes replaced by another transformer winding, called a tertiary winding. The action of a ratio detector is similar to that of a Foster-Seeley discriminator except that the output is equal to the ratio of two voltages rather than the difference between two voltages. When a carrier at the i-f center frequency is received, the voltages across C_4 and C_5 are equal. When the FM signal swings below the center frequency, D_1 conducts more than D_2. The voltage across C_4 increases while the voltage across C_5 decreases. When the FM signal swings above the center frequency, the action reverses. Thus, an audio-frequency voltage corresponding to the frequency swings in the modulated signal is developed across C_5 and R_1.

Notice that the voltage across C_6 is the sum of the voltages across C_4 and C_5. As the frequency changes, one of these voltages increases and the other decreases. Thus, the voltage across C_6 remains fairly constant. Sudden changes in the amplitude of the incoming signal have little effect on the output voltage because the large capacitance of C_6 holds the total voltage across C_4 and C_5 constant. Because only the ratio of the voltages across C_4 and C_5 can change the output voltage, it is known as a ratio detector.

FM STEREO RECEPTION

Both stereophonic (two-channel) and monophonic (single-channel) FM receivers contain essentially the same superheterodyne and tuning circuitry from the antenna terminals through the detector stage. While the stereo receiver must utilize two audio amplifiers, one for the left channel and one for the right channel, the main feature of the stereo receiver is the stereo demultiplexing circuit between the FM detector and the audio amplifier stages. Demultiplexing is the reverse of multiplexing; it separates the multiplexed signals from the demodulated signals coming from the detector.

Figure 2-10 shows a graph of the composite stereo signal at the output of the FM detector. The signal includes the conventional audio signal approximately 30 Hz to 15 kHz, which provides normal reception for monophonic receivers. This is labeled L + R because it contains both right and left microphone signals from the studio. There is also a 19-kHz pilot signal and the upper and lower AM sidebands of the stereo difference (L − R) signal. These frequencies are necessary to obtain stereo reproduction.

The following Practice Exercise questions cover the subjects which you have just studied. They are:

AM DETECTION

AN AM RADIO SCHEMATIC

SINGLE SIDEBAND DETECTION

FM DETECTION

THE FOSTER-SEELEY DISCRIMINATOR

92. Why are capacitors C_2 and C_4 ganged together in the circuit of Figure 2-4?

93. The primaries of T_3, T_4 and T_5 in Figure 2-4 are tuned to (a) the local oscillator frequency, (b) the incoming carrier frequency, (c) the difference frequency between the local oscillator frequency and the incoming carrier frequency.

94. In Figure 2-4, what is the Q_1 frequency converter stage called?

95. What is the name of the process of adjusting trimmer capacitors and i-f transformers so that the respective tank circuits are tuned to the correct frequencies?

96. What is the major difference between double sideband AM detection and SSB detection.

97. How does the required i-f bandwidth of an SSB receiver compare to that of a standard AM communications receiver?

98. In an FM broadcast receiver, the intermediate carrier frequency is usually (a) 455 kHz, (b) 10.7 MHz, (c) 88 MHz.

99. In an FM broadcast receiver, a suitable i-f bandwidth would be about (a) 20 kHz, (b) 75 kHz, (c) 200 kHz.

100. In which type of broadcast receiver, AM or FM, is the wiring and parts layout generally more critical? Why?

101. Refer to the S curve of Figure 2-8. The knees of the S curve should be equally spaced above and below f_r, the i-f carrier frequency. True or False?

102. What is the function of the limiter stage in an FM receiver using a Foster-Seeley discriminator?

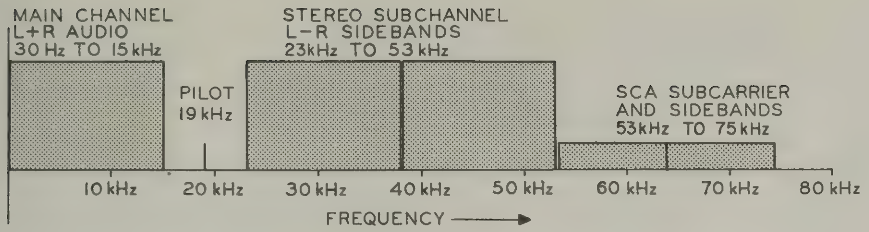


Figure 2-10

Notice that the L − R sidebands extend from 23 kHz to 53 kHz. The notch in the middle of the L − R sidebands shows that the original 38-kHz subcarrier that was used to generate these sidebands is suppressed at the studio. Therefore, it must be reinserted at the receiver to demodulate the L − R stereo difference signal sidebands.

The SCA (Subsidiary Communications Act) subcarrier and sidebands may extend from 53 kHz to 75 kHz when the station is transmitting stereo material. The SCA signal, when it is transmitted, is used for special program music that is not part of either the stereophonic or monophonic programs. The SCA signal is therefore removed by a filter network.

The stereo section of an FM stereo receiver performs the following functions:

1. Separates the desired components of the composite signal. (In the ordinary home-entertainment receiver, the SCA subcarrier and its sidebands are discarded.)

2. Amplifies and doubles the 19-kHz pilot signal to generate a 38-kHz subcarrier. The 38-kHz subcarrier is applied to the L − R detector.

3. Detects the L − R stereo difference signal sidebands to obtain the L − R audio signal.

4. Adds the L − R audio signal to the L + R audio signal to produce left channel and right channel audio signals for stereo listening.

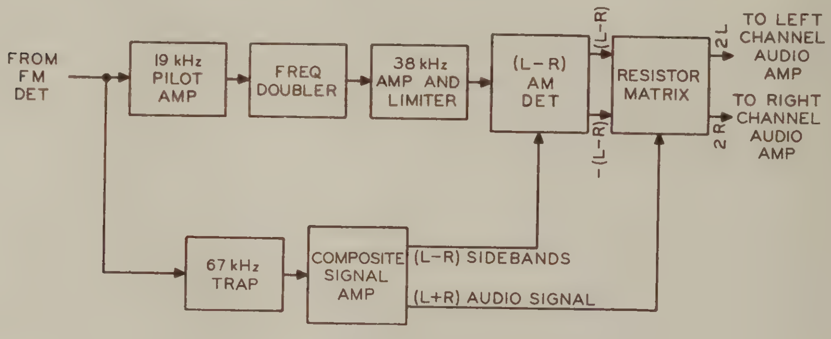
The L − R detector actually produces two outputs—an L − R signal and a −(L − R) or −L + R signal. Adding the L − R signal to the main channel, or L + R, signal produces the L or left channel audio signal. This addition can be represented mathematically as:

$$(L - R) + (L + R) = L - R + L + R = 2L.$$

Notice that mathematically the addition results in 2L. This simply means that the output has twice the amplitude of an L signal in either the L + R or L − R signal. Adding the −(L − R) or −L + R signal to the main channel, or L + R, signal produces the R or right channel audio signal. This addition can be represented mathematically as:

$$-(L - R) + (L + R) = -L + R + L + R = 2R.$$

Again, the 2R indicates that the output has twice the amplitude of an R signal in either the L + R or L − R signals. Thus, by combining the L + R and L − R signals, both the original left (L) and right (R) signals can be recovered at the same time for stereo listening. The L + R signal provides monaural listening when the station is broadcasting a monophonic signal.



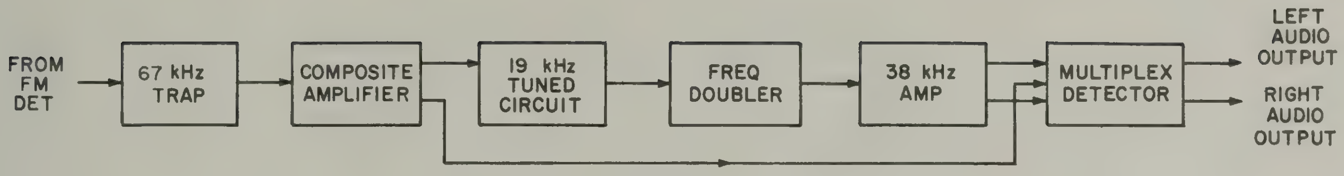
A

Figure 2-11

Figure 2-11A is a block diagram of a typical stereo demultiplexing circuit. The signal from the FM detector output is applied to a 19-kHz pilot signal amplifier. The output of this amplifier is doubled in frequency by a frequency doubler circuit and applied to a 38-kHz amplifier and limiter. This stage limits the amplitude of the 38-kHz subcarrier to the amplitude required for the proper operation of the (L − R) AM detector. In some stereo receivers, the 19-kHz pilot signal is used to synchronize a 38-kHz oscillator to produce the 38-kHz subcarrier.

In the lower section of Figure 2-11A, the FM detector output is applied to a composite signal amplifier through a 67-kHz trap. The 67-kHz trap removes the SCA subcarrier and sidebands. The composite signal amplifier has two outputs. One output is applied to the (L − R) AM detector. There, it is heterodyned with the 38-kHz subcarrier to produce an L − R audio signal and a −(L − R) audio signal. The other output of the composite signal amplifier is the L + R audio signal which is applied to a resistor matrix. This is simply a resistor network where the L + R audio signal is added to the L − R and −(L − R) audio signals to produce the left channel and right channel audio signals as previously explained.

During monophonic broadcasts, the 19-kHz pilot amplifier and (L − R) AM detector are inactive. The conventional audio signal (L + R) is the only signal applied to the matrix, and it is fed to both the right channel and left channel amplifiers.



B

Figure 2-11

Figure 2-11B is the block diagram of another stereo demultiplexing circuit, which is probably the most popular system in current use. The entire signal from the FM detector is fed through a 67-kHz trap, which eliminates the SCA signal, to the composite amplifier. From one output of this amplifier, the 19-kHz pilot signal is doubled in frequency to form the 38-kHz subcarrier signal. After being amplified, the 38-kHz subcarrier signal is applied to the multiplex detector.

The second output of the composite amplifier is the L + R audio signal and the L − R sidebands. (The 19-kHz pilot signal has been extracted by the 19-kHz tuned circuit.) The composite signal is also applied to the multiplex detector where it is mixed with the 38-kHz subcarrier signal to produce the left audio signal and the right audio signal.

Figure 2-12 is a schematic diagram of the stereo demultiplexing circuit represented by the block diagram of Figure 2-11B. The composite multiplex signal from the ratio detector is fed through the 67-kHz trap (L_{15}, C_{52}, C_{53}, L_{16} and C_{54}) to the base of the composite amplifier, TR_9. The entire signal is amplified and developed across the L_{17} primary and R_{61} in the TR_9 collector circuit. Because L_{17} is tuned to 19 kHz, the 19-kHz pilot signal is developed across L_{17}, while the remainder of the signal (L + R audio and L − R sidebands) is developed across R_{61}.

The 19-kHz pilot signal is taken from the L_{17} secondary and applied to a frequency doubler made up of D_9 and D_{10}, which is essentially a full-wave rectifier. Since the ripple frequency of a full-wave rectifier is double the source frequency, the signal applied to the base of TR_{10} is 2 × 19 kHz, or 38 kHz. After being amplified by TR_{10}, this signal is the 38-kHz subcarrier sinewave that is developed across L_{18} and applied to the multiplex detector diodes (D_{12}, D_{13}, D_{14} and D_{15}).

In the collector circuit of transistor TR_9, the L + R audio signal and the L − R sidebands are developed across R_{61} and coupled through C_{60} to the center tap of the L_{18} secondary. These signals are then applied through the L_{18} secondary to the multiplex detector diodes, together with the 38-kHz subcarrier signal.

Probably the best way to analyze the multiplex detector circuitry is to start with a monophonic broadcast. Neither the 19-kHz pilot signal nor the L − R sidebands are transmitted for monophonic reception. Therefore, the only signal applied to the multiplex detector diodes is the L + R audio signal. Diode D_{15} conducts on the negative alternations of the L + R audio signal, while diode D_{14} conducts on the positive alternations, and the entire L + R audio signal appears at the left channel output. Diodes D_{12} and D_{13} conduct in the same fashion, and the entire L + R audio signal also appears at the right channel output.

During a stereo broadcast, the 38-kHz subcarrier sinewave and the L − R sidebands are added to the L + R audio signal at the input to the multiplex detector diodes. The L + R audio signal is processed exactly as just described, while the L − R sidebands and the properly phased 38-kHz subcarrier signal are heterodyned by D_{15} and D_{14} to produce the L − R signal at the left output. Because of the way the multiplex detector diodes (D_{12} and D_{13}) are connected, they simultaneously produce the −(L − R) signal at the right channel output. The addition of L + R to the L − R signal causes a left channel signal at the left output; the addition of L + R to the −(L − R) causes a right channel signal at the right output.

The only portion of Figure 2-12 remaining to be explained is the stereo indicator circuitry of transistor TR_{11}. In the L_{17} secondary, the 19-kHz pilot signal causes conduction of D_9 and D_{10}, which forward biases the base of TR_{10}. This causes collector current in TR_{10} through the L_{18} primary, R_{66}, and the base-emitter junction of TR_{11}. Therefore, the TR_{10} collector current is the TR_{11} base current, which, in turn, causes TR_{11} collector current. The TR_{11} collector current through the Stereo Indicator, PL_1, causes it to glow.

During a monophonic broadcast, there is no 19-kHz pilot signal. Diodes D_9 and D_{10} do not conduct, TR_{10} is not forward biased and the TR_{10} collector current drops to zero. With no TR_{10} collector current, there is no TR_{11} base current. The TR_{11} collector current therefore drops to zero, and PL_1 does not glow.

SUMMARY

In the modulation process a characteristic of a carrier wave, such as amplitude or frequency, is varied in accordance with the modulating signal. At the receiver, the modulating signal is recovered by a reverse process, called demodulation or detection. The diode is the most common device used for AM detection. The basic actions of this type of detector are rectification and filtering.

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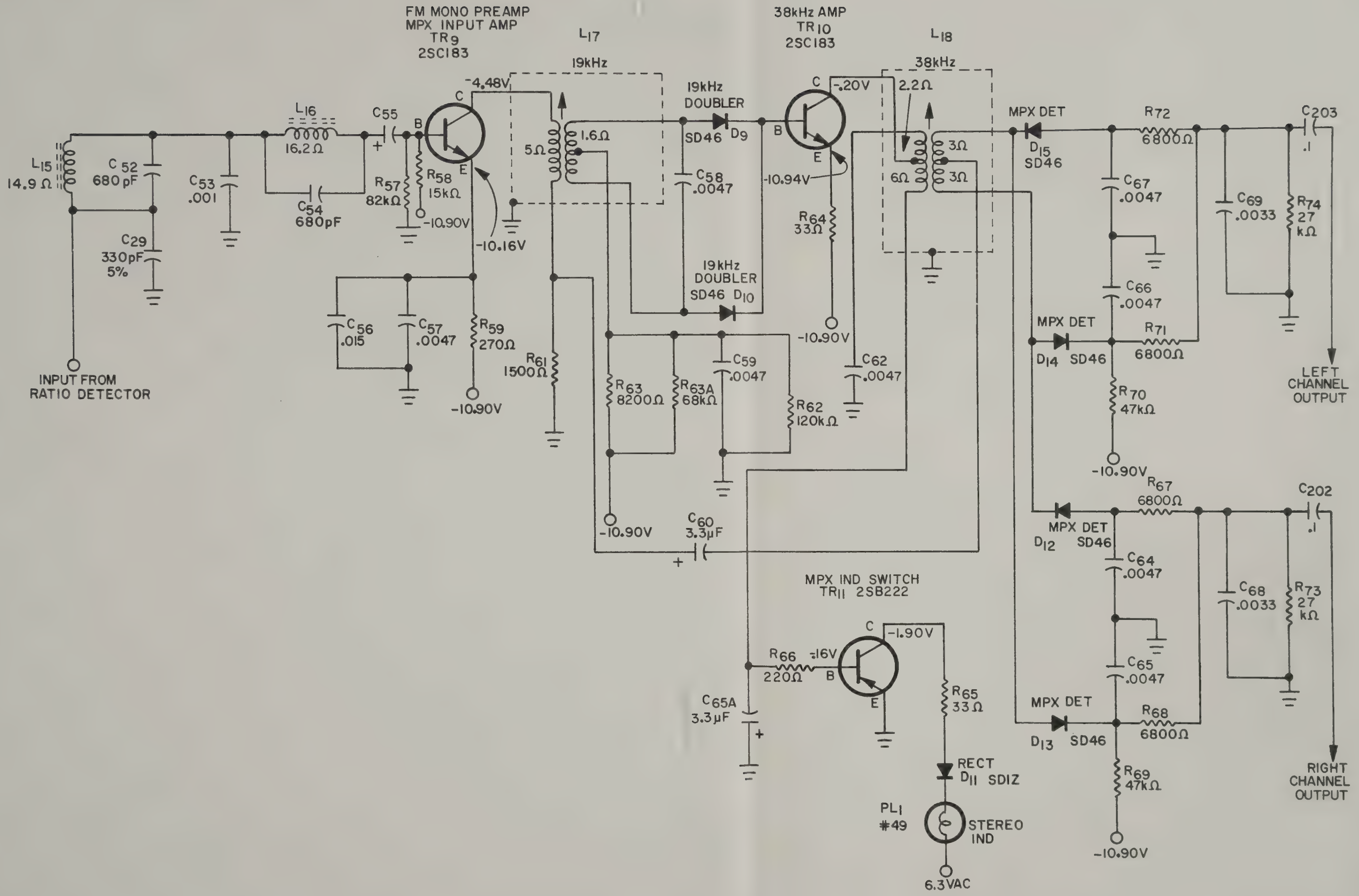
FM MONO PREAMP
MPX INPUT AMP
TR9
2SC183
L17
19kHz
38kHz AMP
TR10
2SC183
L18
38kHz
-4.48V
C
B
E
19kHz DOUBLER
SD46 D9
C58 .0047
-.20V
2.2Ω
5Ω
1.6Ω
-10.94V
E
6Ω
3Ω
3Ω
R64 33Ω
MPX DET
D15 SD46
R72 6800Ω
C203 .1
L16 16.2Ω
C55
L15 14.9 Ω
C 52 680 pF
C53 .001
C54 680pF
R57 82kΩ
R58 15kΩ
-10.90V
-10.16V
C29 330pF 5%
C67 .0047
C69 .0033
R74 27 kΩ
C66 .0047
19kHz DOUBLER
SD46 D10
-10.90V
MPX DET
D14 SD46
R71 6800Ω
C56 .015
C57 .0047
R59 270Ω
R61 1500Ω
R63 8200Ω
R63A 68kΩ
C59 .0047
R62 120kΩ
C62 .0047
INPUT FROM RATIO DETECTOR
-10.90V
R70 47kΩ
LEFT CHANNEL OUTPUT
-10.90V
-10.90V
R67 6800Ω
C202 .1
C60 3.3μF
MPX DET
D12 SD46
C64 .0047
C68 .0033
R73 27 kΩ
MPX IND SWITCH
TR11 2SB222
C
-1.90V
R66 220Ω
-.16V
B
E
C65 .0047
C65A 3.3μF
R65 33Ω
MPX DET
D13 SD46
R68 6800Ω
RECT
D11 SDIZ
R69 47kΩ
RIGHT CHANNEL OUTPUT
PL1 #49
STEREO IND
6.3VAC
-10.90V

Figure 2-12

The following Practice Exercise questions cover the subjects which you have just studied. They are:

FM DETECTION

THE RATIO DETECTOR

FM STEREO RECEPTION

103. Is it necessary to precede a ratio detector with a limiter?

104. Give two ways to distinguish a ratio detector from a Foster-Seeley discriminator.

105. The stereo section of an FM stereo receiver obtains its input directly from (a) the frequency converter stage, (b) the FM detector stage, (c) the audio amplifier stage.

106. During reception of a stereo multiplex broadcast, at least three distinct signals are present at the output of the FM detector equipped to receive FM stereo. What are these three signals?

107. At the output of the FM detector, the L + R signal has approximate frequency limits of (a) 30 Hz to 15 kHz, (b) 23 kHz to 53 kHz, (c) 59.5 kHz to 74.5 kHz.

108. At the output of the FM detector, the L − R sidebands have frequency limits of (a) 30 Hz to 15 kHz, (b) 23 kHz to 53 kHz, (c) 59.5 kHz to 74.5 kHz.

109. Show how the addition of the L + R signal to the L − R signal produces a left channel audio signal equal to 2L.

110. Show how the addition of the L + R signal to the −(L − R) signal produces a right channel audio signal equal to 2R.

111. How is the 38-kHz subcarrier produced in the stereo demultiplexing circuit of Figure 2-11B? Give another way of producing the 38-kHz subcarrier.

112. What signals are removed from the composite stereo signal by the 67-kHz trap?

113. In a conventional monophonic FM receiver, what use is made of the 19-kHz pilot signal and the L − R sidebands?

114. In the circuit of Figure 2-12, TR_{11} conducts during a (a) stereo broadcast, (b) monophonic broadcast.

115. In the circuit of Figure 2-12, what is the resonant frequency of L_{17}? Of L_{18}?

116. The frequency doubler circuit of Figure 2-12 acts like a (a) half-wave rectifier, (b) full-wave rectifier.

Single sideband transmission is much like ordinary AM transmission except that the carrier and one sideband are removed or suppressed at the transmitter. Only one sideband is transmitted. Thus, the carrier must be reinserted at the receiver to demodulate an SSB signal. The carrier is produced at the receiver by an oscillator called a BFO.

Two of the most commonly used FM detector circuits are the Foster-Seeley discriminator and the ratio detector. The Foster-Seeley discriminator circuit looks much like the ratio detector circuit. They can be easily distinguished from each other, however. In the Foster-Seeley discriminator, the two diodes are connected series-opposing, while in the ratio detector they are connected series-aiding. Also, in the ratio detector, a large electrolytic capacitor is connected in series with the diodes.

IMPORTANT DEFINITIONS

ALIGNMENT—The process of adjusting the trimmer capacitors and the i-f transformers so that the respective tank circuits are tuned to the correct frequencies.

AMPLITUDE MODULATION (AM)—A type of modulation in which the amplitude of the carrier varies in step with the amplitude of the modulating signal.

AUDIO CORRECTOR—A correction circuit used to allow the frequency deviation of an FM signal to be proportional only to the amplitude of the modulating signal.

AUTODYNE CONVERTER—A type of frequency converter in which a single transistor or vacuum tube simultaneously performs the functions of the local oscillator and mixer.

AUTOMATIC FREQUENCY CONTROL (AFC)—A frequency stability circuit used with the master oscillator of an FM system to insure that the master oscillator center frequency is maintained.

AUTOMATIC VOLUME CONTROL (AVC)—A radio circuit used to reduce excessive changes in volume due to changes in the strength of the incoming signal.

BALANCED MODULATOR—A circuit used to suppress the carrier and produce sidebands in a suppressed carrier AM or FM system.

CARRIER—The sinewave of single frequency (usually r-f) and constant amplitude to which the modulating signal is applied.

CARRIER DEVIATION—The frequency change above or below the unmodulated center frequency as a result of modulation in an FM system. Also called FREQUENCY DEVIATION.

CENTER FREQUENCY—The frequency of the unmodulated carrier in an FM system.

COLLECTOR MODULATION—A system of modulation in which the modulating signal is applied to the collector of the transistor in the modulated stage.

CONTROL GRID MODULATION—The modulation process in which the modulating voltage is applied to the control grid of the tube of the modulated stage.

DEMODULATION—The process by which the modulating signal is recovered from the sidebands. Also called DETECTION.

IMPORTANT DEFINITIONS (Continued)

DEMODULATOR—A circuit used to recover the modulating signal from the sidebands. Also called a DETECTOR.

DETECTION—See DEMODULATION.

DETECTOR—See DEMODULATOR.

DIRECT FM—A system of FM in which the frequency of the master oscillator is deviated directly by the modulating signal.

DOUBLE SIDEBAND SUPPRESSED CARRIER TRANSMISSION (DSSC)—A type of transmission in which the carrier is removed and only the sideband frequencies and a reference signal are normally transmitted.

DOUBLE SIDEBAND TRANSMISSION (DS)—The system of transmission where the carrier frequency and all of the sideband frequency components are transmitted with their normal amplitudes. This is the standard type of AM broadcast transmission.

EMITTER MODULATION—A transistorized modulation circuit in which the modulating signal is applied to the emitter of the transistor of the modulated stage.

FOSTER-SEELEY DISCRIMINATOR—A type of FM demodulator which contains two diodes that are connected series-opposing across a transformer secondary.

FREQUENCY DEVIATION—See CARRIER DEVIATION.

FREQUENCY MODULATION (FM)—A type of modulation in which the frequency of the carrier varies in step with the amplitude of the modulating signal.

FREQUENCY MULTIPLIER—A circuit which has its output tuned to a harmonic of its input so that the output is some whole-number multiple of the input frequency.

HIGH-LEVEL MODULATION—Modulation produced in the plate or collector circuit of the final r-f stage of a transmitter.

INDIRECT FM—A system of FM in which the master oscillator frequency is held constant and the signal is phase modulated in a later stage.

INTERMEDIATE FREQUENCY—A frequency equal to the difference between the local oscillator frequency and that of the r-f carrier received by a radio receiver. This frequency is obtained in the converter

IMPORTANT DEFINITIONS (Continued)

stage of the receiver. It is used to provide information signal amplification at frequencies lower than the r-f carrier.

LIMITER—A special type of amplifier stage which limits the amplitude of the output to some fixed value.

LOCAL OSCILLATOR—Part of a radio-frequency converter circuit which is used in a superheterodyne receiver to obtain the desired intermediate frequency.

LOW-LEVEL MODULATION—Modulation produced at any point before the plate or collector circuit of the final r-f stage.

MAIN CHANNEL—A band of frequencies from about 30 to 15,000 Hz which frequency modulates the main carrier in a stereo FM system.

MIXER—A stage in a superheterodyne receiver in which the incoming signal is combined with the signal from a local oscillator to produce the required intermediate frequency.

MODULATED AMPLIFIER—The r-f amplifier stage in which the information signal modulates the radio-frequency carrier.

MODULATED STAGE—See MODULATED AMPLIFIER.

MODULATING SIGNAL—The information signal used to modulate a carrier.

MODULATION—The process of impressing information on a carrier.

MODULATION ENVELOPE—An outline enclosing the total modulated wave. The modulation envelope shape represents the waveform of the information conveyed by the signal.

MODULATION INDEX—In FM systems, the ratio of the carrier frequency deviation to the frequency of the modulating signal.

MODULATION PERCENTAGE—In AM systems, 100% modulation causes the carrier envelope to vary from zero to twice its unmodulated value. In FM systems, the ratio of the actual frequency deviation to the frequency deviation defined as 100% modulation. For FM broadcast stations, a frequency deviation of ±75 kHz is defined as 100% modulation.

MODULATOR—The stage that supplies the signal to be modulated.

IMPORTANT DEFINITIONS (Continued)

MULTIPLEX TRANSMISSION—The simultaneous transmission of two or more modulating signals within a single channel using one main carrier.

NARROW BAND FM—A service FM band where the deviation for 100% modulation is small (±5 kHz), as compared with the FM broadcast band where a ±75-kHz deviation is required for 100% modulation.

OVERMODULATION—Amplitude modulation greater than 100%. The result is distortion and a wider-than-normal bandwidth.

PHASE MODULATION (PM)—A type of FM transmission system which uses the modulating signal to shift the phase of the r-f signal.

PILOT SIGNAL—In stereo FM, a 19-kHz sinewave serving as a control signal in the reception of FM stereophonic broadcasts.

PLATE MODULATION—The modulation method in which the modulating voltage is applied to the plate circuit of the tube in the modulated stage.

RATIO DETECTOR—A type of FM demodulator which contains two diodes that are connected series-aiding across a transformer secondary. The ratio detector provides its own limiting action.

REACTANCE TUBE MODULATOR—A circuit in which a vacuum tube is made to act as a variable inductance or a variable capacitance.

SCREEN GRID MODULATION—The modulation process in which the modulating voltage is applied to the screen grid of the tube in the modulated stage.

SERRASOID PHASE MODULATOR—A modulator used in indirect FM systems which produces a sawtooth waveform at the master oscillator frequency. The modulating a-f signal then phase modulates the sawtooth waveform.

SIDEBAND PAIR—A term referring to the combination of the lower and upper sideband signals.

SIDEBAND SIGNALS—Signals representing information which occupy the upper and lower sidebands.

SIDEBANDS—Bands of frequencies above and below the carrier frequency which contain the information being transmitted. They are produced by modulation of the carrier; the sum of the carrier frequency and the modulating frequencies forms the upper sideband, while the difference between these frequencies forms the lower sideband.

IMPORTANT DEFINITIONS (Continued)

SINGLE SIDEBAND TRANSMISSION (SSB)—A system in which only one sideband is transmitted. The r-f carrier and one of the two sidebands are suppressed at the transmitter.

STEREO SUBCHANNEL—The band of frequencies from 23 kHz to 53 kHz containing the sidebands of the stereophonic subcarrier. These sidebands are often called the L − R sidebands.

SUBCARRIER—A low-frequency carrier used to modulate a high-frequency carrier in multiplex transmission systems.

SUPERHETERODYNE RECEIVER—A type of receiver where the incoming r-f carrier is converted to the required intermediate frequency.

SUPPRESSOR GRID MODULATION—The modulation process in which the modulating voltage is applied to the suppressor grid of the tube in the modulated stage.

TUNED RADIO-FREQUENCY (TRF) RECEIVER—A type of receiver which uses two or three r-f amplifier stages, a detector, and one or more audio-frequency amplifier stages. All of the r-f stages are tuned circuits which require simultaneous adjustment in order to select the desired broadcast station frequency.

ESSENTIAL SYMBOLS AND EQUATIONS

M	Percentage of modulation divided by 100	
P_C	Carrier power	(watts)
P_{SB}	Total sideband power	(watts)
X	Lower peak amplitude of an Amplitude-Modulated wave	(inches, centimeters, etc.)
Y	Upper peak amplitude of an Amplitude-Modulated wave	(inches, centimeters, etc.)

$$\% \text{ MODULATION} = \frac{Y - X}{Y + X} \times 100 \qquad (1)$$

$$P_{SB} = \frac{M^2}{2} P_C \qquad (2)$$

$$\text{Modulation Index} = \frac{\text{Carrier Frequency Deviation}}{\text{Frequency of Modulating Signal}} \qquad (3)$$

PRACTICE EXERCISE SOLUTIONS

1. To add information which is to be transmitted.

2. No—A nonlinear element is needed to obtain modulation.

3. L_1 and C_1 form a resonant circuit which fills in the negative portions of the voltage waveform so that the output current waveform of Figure 1-4 becomes the voltage waveform of Figure 1-5.

4. False—A resonant circuit with an extremely high Q would tend to fill in the low spots in the modulation envelope. This would cause the modulation of the carrier to be distorted or lost.

5. (a) nonlinear device.

6. The greater the amplitude of the modulating signal, the greater the amplitude of the sideband signals.

7. 2 kHz.—The upper sideband signal is 1 kHz above the carrier frequency and the lower sideband signal is 1 kHz below the carrier frequency. Therefore, the bandwidth required to pass both signals is 2 kHz.

8. 2 kHz.—Bandwidth is determined by the frequency of the modulating signal, not by the carrier frequency.

9. 25%.— % Modulation $= \dfrac{Y - X}{Y + X} \times 100$

$$= \frac{5 - 3}{5 + 3} \times 100$$

$$= \frac{2}{8} \times 100 = 25\%.$$

10. False—100% modulation is the maximum normally used.

11. (a) always the same.

12. Three.—One pair for each modulating signal.

13. The total sideband power is 25 kW; the power in each sideband is 12.5 kW.

$$P_{SB} = \frac{M^2}{2} P_C = \frac{(1)^2}{2} 50 \text{ kW} = 25 \text{ kW}.$$

Each sideband is half of this or 12.5 kW.

PRACTICE EXERCISE SOLUTIONS (Continued)

14. (c) 150 watts.—The total radiated power is equal to the carrier power plus the power of the sidebands. In this case,

$$P_{SB} = \frac{(1)^2}{2} \text{ 100 watts} = \text{50 watts.}$$

Carrier Power = 100 watts. Total Radiated Power = Carrier Power + Sideband Power = 100 + 50 = 150 watts.

15. False—This describes the indirect method. The direct method determines the power by measuring the current in the antenna feed lines and the antenna resistance.

16. It is the product of the dc plate voltage and average plate current of the final stage.

17. (b) the plate or collector circuit of the final stage that feeds the antenna.—Modulation before this stage is considered to be low-level modulation.

18. Low-level modulation could take place at any point preceding the final amplifier stage.

19. False—Modulation takes place in the modulated stage, and the modulating signal is supplied by the modulator.

20. True

21. (b) high-level modulation.

22. (c) 100%.

23. Class C operation can be used in these r-f amplifiers for greater efficiency.

24. False—The suppressor grid is connected through a modulation transformer to a dc bias supply.

25. Control grid modulation requires less modulating power than that required by plate modulation.

26. False—Either high-level or low-level modulation can be used with transistorized circuits.

27. The low-level modulator provides the least amount of power for 100% modulation.

PRACTICE EXERCISE SOLUTIONS (Continued)

28. The modulated amplifier is often operated Class C in these systems.

29. It is not necessary to transmit carrier power. A final amplifier with lower power can then be used.

30. A balanced modulator is usually used.

31. (c) both sidebands without a carrier.

32. True—Compared to standard double sideband transmission, a single sideband transmitter requires additional circuits to remove the carrier and one sideband.

33. (c) the smaller space required in the frequency spectrum.

34. True

35. True

36. Electrical interference usually causes amplitude modulation of the carrier.

37. The frequency of the carrier.

38. (a) amplitude.

39. The modulating signal amplitude has no effect on the carrier amplitude. The modulating signal amplitude affects the frequency of the carrier, not its amplitude.

40. (b) frequency.

41. False—The modulating signal frequency affects only the rate of carrier deviation and not the amount.

42. Limiting the carrier deviation provides for a maximum number of stations without interference.

43. ±75 kHz.

44. (c) ±5 kHz.

45. True—For TV broadcast stations a carrier deviation of ±25 kHz is designated as 100% modulation. Half this deviation (±12.5 kHz) is 50% modulation.

46. False—A large number of sideband signals are produced.

PRACTICE EXERCISE SOLUTIONS (Continued)

47. 4 kHz.

48. 45 kHz.

49. The modulation index is used to determine the number of significant sideband pairs.

50. 2.5—The modulation index is determined as follows:

$$\text{Modulation Index} = \frac{25}{10} = 2.5$$

51. (a) increases.

52. The total radiated power remains constant.

53. (a) direct FM system.

54. ±7 kHz.

55. Maintaining oscillator stability and obtaining linear deviation.

56. The output circuit is tuned to the second harmonic of the input circuit.

57. Center frequency = 97.2 MHz; carrier deviation = ±54 kHz.—The total frequency multiplication is $2 \times 3 \times 3 \times 3 = 54$. The center frequency is therefore $1.8 \times 54 = 97.2$ MHz and the carrier deviation is ± 1 kHz $\times 54 = \pm 54$ kHz.

58. False—The AFC circuit keeps the master oscillator at the correct center frequency.

59. True

60. (a) independent of the modulating signal frequency.

61. The audio corrector makes the carrier deviation proportional to only the modulating signal amplitude.

62. C_5 and L_2.

63. (a) inductance.

64. The V_1 plate current lags the plate voltage.

65. True

PRACTICE EXERCISE SOLUTIONS (Continued)

66. In the indirect FM system, the master oscillator is not modulated, which results in improved stability.

67. The frequency deviation is so small that a large multiplication is needed to obtain the desired frequency deviation.

68. (b) two.

69. A subcarrier is a carrier lower in frequency than the main carrier.

70. The L − R audio signal amplitude modulates the subcarrier to form L − R sidebands. The L − R sidebands, in turn, frequency modulate the main FM carrier.

71. The 19-kHz pilot is transmitted so that the receiver can process the L − R signal to obtain proper stereophonic reception.

72. (c) 67 kHz.

73. The modulating signal varies the frequency of the carrier. The amplitude of the modulating signal determines the amount of deviation, or frequency swing, and the frequency of the modulating signal determines the rate at which the frequency varies.

74. The modulating signal varies the amplitude of the carrier. The amplitude of the modulating signal determines the maximum and minimum amplitudes of the modulated carrier. The frequency of the modulating signal determines the frequency at which the amplitude of the carrier varies.

75. A conventional AM signal is made up of the carrier and both sidebands. An SSB signal consists of only one sideband.

76. A transmitted signal will not directly actuate a speaker or other reproduction device. The modulating signal must be recovered from the transmitted signal by a demodulator.

77. To recover the modulating signal in its original form.

78. The demodulator must be capable of recovering the modulating signal originally applied to the carrier. Each type of modulation requires a particular type of demodulator.

79. A diode.—Either a vacuum tube or semiconductor diode can be used as an AM detector.

80. Rectification and filtering.—The diode rectifies the high-frequency ac

PRACTICE EXERCISE SOLUTIONS (Continued)

signal to produce a pulsating dc signal. The filter removes the pulsations and produces an output proportional to the original modulating signal.

81. C_3 filters, or removes, high-frequency carrier variations from the rectified signal. Thus, only the modulation signal variations appear across R_1.

82. Because the potentiometer also serves as the volume control of the receiver. This combines two functions in one component.

83. False—The dc is blocked by capacitor C_4. Only variations in level, called the ac component, are passed.

84. 455 kHz.

85. To provide the local oscillator signal and to heterodyne (or beat) the local oscillator signal with the incoming r-f signal. Briefly, a converter is both an oscillator and a mixer.

86. 1555 kHz.—The oscillator frequency is 455 kHz above the incoming carrier. Thus, 1100 kHz + 455 kHz = 1555 kHz.

87. Modulated i-f.

88. An audio-frequency signal.

89. (b) 10 kHz.

90. (b) dc.

91. (b) detector.—The basic actions of a diode detector are rectification and filtering. The dc output of the detector is the source of the AVC voltage.

92. They are ganged so that the oscillator frequency will always be 455 kHz above the incoming carrier frequency selected by the tuned input circuit.

93. (c) the difference frequency between the local oscillator frequency and the incoming carrier frequency.—This is the intermediate frequency of the receiver.

94. An autodyne converter.

95. Alignment.

96. To detect (or demodulate) an SSB signal, the carrier must be reinserted.

97. The i-f bandwidth must be only about half as wide in an SSB receiver since only one sideband must be passed through the i-f amplifiers.

PRACTICE EXERCISE SOLUTIONS (Continued)

98. (b) 10.7 MHz.—455 kHz is the intermediate frequency of most standard AM broadcast receivers, and 88 MHz is the lower limit of the FM broadcast band.

99. (c) 200 kHz.—The i-f bandwidth of a standard AM receiver is 20 kHz, and 75 kHz is the frequency deviation of a standard FM carrier at 100% modulation. However, an FM signal contains significant sideband signals in the band from 100 kHz above to 100 kHz below the center frequency.

100. In the FM receiver.—Much higher frequencies are present in the FM broadcast receiver than in the AM broadcast receiver. At these high frequencies, lead (wiring) inductance and capacitance play an important part in circuit operation.

101. True—Otherwise, the output voltage may not be directly proportional to the frequency variations of the input.

102. Since the Foster-Seeley discriminator is sensitive to amplitude modulation, it is preceded by a limiter. The function of the limiter is to maintain a constant amplitude signal to the discriminator regardless of the variations in amplitude of the input signal to the limiter.

103. No—The ratio detector provides its own limiting action.

104. In the ratio detector, the diodes are connected series-aiding, instead of series-opposing, and a large electrolytic capacitor is connected in series with the diodes.

105. (b) the FM detector stage.—In a stereo receiver, the incoming FM signal is converted to an i-f signal, which is then detected in the same way as in a monophonic receiver.

106. The conventional audio signal called the L + R signal, the 19-kHz pilot signal and the stereo difference signal (L − R sidebands). In addition, an SCA (special program music) signal may be present.

107. (a) 30 Hz to 15 kHz.

108. (b) 23 kHz to 53 kHz.

109. $(L - R) + (L + R) = L - R + L + R = 2L$.

110. $-(L - R) + (L + R) = -L + R + L + R = 2R$.

111. By doubling the frequency of the 19-kHz pilot signal. The 38-kHz subcarrier could also be produced by using the 19-kHz pilot signal to synchronize a 38-kHz oscillator.

PRACTICE EXERCISE SOLUTIONS (Continued)

112. The SCA subcarrier and sidebands.

113. None.—These frequencies are above the audio range. They are only used in a stereo demultiplexer, which is designed to handle these frequencies to produce the two channels of audio.

114. (a) stereo broadcast.

115. L_{17} is resonated at 19 kHz and L_{18} at 38 kHz.

116. (b) full-wave rectifier.—The ripple frequency of a full-wave rectifier is twice the source frequency, while the ripple frequency of a half-wave rectifier is the same as the source frequency.

DE VRY INSTITUTE OF TECHNOLOGY
4141 BELMONT AVENUE, CHICAGO, ILLINOIS 60641

ONE OF THE
BELL & HOWELL SCHOOLS

7445A
EXAMINATION CHECK SHEET

1. A - IN AN AMPLITUDE MODULATION SYSTEM, THE INSTANTANEOUS AMPLITUDE OF THE CARRIER SIGNAL IS CONTROLLED BY -- THE AMPLITUDE OF THE MODULATING SIGNAL.
The frequency of the carrier is constant and is predetermined; the frequency of the modulating signal determines the frequency of the signals in the sidebands.

2. D - WHEN TWO SIGNALS OF DIFFERENT FREQUENCIES ARE MIXED IN A NONLINEAR DEVICE SUCH AS A DIODE, THE OUTPUT CONTAINS -- THE SUM AND DIFFERENCE FREQUENCIES AND ONE OR BOTH OF THE ORIGINAL FREQUENCIES.
It is characteristic of nonlinear devices that the output contains the frequencies specified.

3. B - A STANDARD AM BROADCAST STATION HAS A 5000-WATT CARRIER. WHAT IS THE TOTAL RADIATED POWER WHEN THE CARRIER IS MODULATED 100% BY A SINEWAVE SIGNAL? -- 7500 WATTS.
When a carrier is amplitude modulated 100% by a sinewave, the total radiated power increases by 50%.

4. D - WHEN HIGH-LEVEL MODULATION IS USED, WHERE DOES MODULATION OCCUR? -- AT THE OUTPUT ELEMENT OF THE FINAL R-F STAGE.
By definition, high-level modulation must occur at the output element (plate or collector) of the final r-f stage.

5. A - IN FM, THE AMOUNT OF FREQUENCY DEVIATION IS PROPORTIONAL TO THE -- AMPLITUDE OF THE MODULATING SIGNAL.
The FREQUENCY of the modulating signal determines the RATE of deviation. There is no relationship between deviation and carrier power or frequency.

6. C - DEMODULATION IS -- THE PROCESS OF RECOVERING THE MODULATING SIGNAL FROM THE TRANSMITTED SIGNAL.
Detection is the same as demodulation. Modulation is the process of adding a low-frequency information signal to an r-f signal. Demodulation recovers this information signal.

7. B - THE MOST COMMON CIRCUIT USED TO DEMODULATE AN AM SIGNAL IS THE -- DIODE DETECTOR.
The Foster-Seeley discriminator and the ratio detector are used to demodulate an FM signal. The autodyne converter is used to simultaneously perform the functions of the local oscillator and mixer using a single transistor or vacuum tube frequency converter stage.

8. B - IF THERE IS AN INTERMEDIATE FREQUENCY OF 455 kHz AND A LOCAL OSCILLATOR FREQUENCY OF 1655 kHz IN A STANDARD AM BROADCAST RECEIVER, THE FREQUENCY OF THE RECEIVED CARRIER IS -- 1200 kHz.
The frequency of the received carrier is equal to the local oscillator frequency minus the intermediate frequency. 1655 kHz - 455 kHz = 1200 kHz.

9. A - IN FIGURE 2-4, THE PRIMARY PURPOSE OF THE Q_2 AND Q_3 CIRCUITRY IS TO -- AMPLIFY THE I-F SIGNAL.
Converter Q_1 develops the oscillator signal, D_1 converts the i-f signal to the audio signal, and the output of R_{12} is applied to the audio amplifier.

10. C - IN FIGURE 2-12, THE OUTPUT OF THE TR_{10} IS -- THE 38-kHz SUBCARRIER SIGNAL.
The composite multiplex signal, including the L - R sidebands, is developed across R_{61} in the TR_9 collector circuit, while the 19-kHz pilot signal is developed across L_{17}.

QUESTIONS

IMPORTANT—These instructions **MUST** be accurately followed to avoid loss, or errors in grading.

Indicate your answer on this sheet by filling in the box for the most correct answer to each question, as illustrated in the example below.

When all questions have been answered, place the answer card in the proper position to line up the boxes on the card with the boxes on the sheet.

Next, copy the complete lesson code into the space provided on the card, and fill in the answer boxes to correspond with those previously filled in on this sheet.

Before mailing, be certain your correct student number, name and address appear on the card.

LESSON CODE
7445A

Example: A young cow is called a

A ☐ B ☐ C ■ D ☐

(A) puppy. (B) kitten. (C) calf. (D) colt.

1. A ☒ B ☐ C ☐ D ☐

In an amplitude modulation system, the instantaneous amplitude of the carrier signal is controlled by
(A) the amplitude of the modulating signal. (B) the frequency of the carrier. (C) the frequency of the modulating signal. (D) the frequency of the sidebands.

2. A ☐ B ☐ C ☐ D ☒

When two signals of different frequencies are mixed in a nonlinear device such as a diode, the output contains
(A) the oscillator frequency only. (B) only the difference between the original signals. (C) only the sum of the original signals. (D) the sum and difference frequencies and one or both of the original frequencies.

3. A ☐ B ☒ C ☐ D ☐

A standard AM broadcast station has a 5000-watt carrier. What is the total radiated power when the carrier is modulated 100% by a sinewave signal?
(A) 8750 watts. (B) 7500 watts. (C) 5000 watts. (D) 10,000 watts.

4. A ☐ B ☐ C ☐ D ☒

When HIGH-LEVEL modulation is used, where does modulation occur?
(A) At any point where r-f is at a relatively high level. (B) At any element of the final r-f stage. (C) At the input element of the final r-f stage. (D) At the output element of the final r-f stage.

5. A ☒ B ☐ C ☐ D ☐

In FM, the AMOUNT of frequency deviation is proportional to the
(A) amplitude of the modulating signal. (B) frequency of the carrier. (C) frequency of the modulating signal. (D) transmitted power of the carrier.

6. A ☐ B ☐ C ☒ D ☐

Demodulation is
(A) the opposite of detection. (B) the same as modulation. (C) the process of recovering the modulating signal from the transmitted signal. (D) the process of generating the modulating signal for the transmitted signal.

7. A ☐ B ☒ C ☐ D ☐

The most common circuit used to demodulate an AM signal is the
(A) Foster-Seeley discriminator. (B) diode detector. (C) ratio detector. (D) autodyne converter.

8. A ☐ B ☒ C ☐ D ☐

If there is an intermediate frequency of 455 kHz and a local oscillator frequency of 1655 kHz in a standard AM broadcast receiver, the frequency of the received carrier is
(A) 910 kHz. (B) 1200 kHz. (C) 1655 kHz. (D) 10.7 MHz.

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In Figure 2-4, the primary purpose of the Q_2 and Q_3 circuitry is to
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10. A ☐ B ☐ C ☒ D ☐

In Figure 2-12, the output of TR_{10} is (A) the composite multiplex signal. (B) the 19-kHz pilot signal. (C) the 38-kHz subcarrier signal. (D) the L − R sidebands.

COMMUNICATIONS SYSTEMS

7450

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Advances in circuit technology have made possible great reductions in the size and weight of TV receivers. The portable receiver shown above is a typical example.

Courtesy RCA

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The easiest way to get to the top
is to get to the bottom of things.
—The Youngstown Bulletin

COMMUNICATIONS SYSTEMS

The primary purpose of a communications system is to convey information from one point to another. At short distances, speech can be conveyed between two people by sound waves (direct audible sound). These two persons may continue to talk to each other as long as they are close enough to clearly hear each other.

As the distance between the person talking and the listener is increased, a point is reached where voice communication is impossible. Communications can be resumed by using a public address system. This system increases the sound level to cover a greater distance. But this, too, has a limited range. Communication by telephone is our next choice. This method, however, requires the use of wires which limits its use. This limitation is overcome by RADIO COMMUNICATION, which provides greater flexibility because it is wireless. Radio enables us to communicate with remote ships, aircraft, satellites and other mobile stations.

Basically, there are two types of communications systems. These are referred to as one-way and two-way systems. In a one-way communications system information is conveyed from a sending point to a receiving point, but not in the opposite direction. Radio and television broadcasts are examples of one-way communications. We can receive the radio or TV programs, but we cannot communicate directly back to the station. With a two-way communications system, we are able to convey information back and forth between two points. Each station has a sending and receiving unit.

Radio communications systems convey information through space by means of radio waves. This information being conveyed by the radio waves is referred to as **INTELLIGENCE.**

Many types of intelligence can be transmitted. Some radio waves may contain code or speech. Others may contain music or picture intelligence. The device used to transmit this intelligence is called a TRANSMITTER. The device used to receive the transmitted intelligence is called a RECEIVER.

BROADCAST SYSTEMS

For the most part, broadcast systems refer to one-way communications systems. Each system consists of a radio transmitter, called the station, and one or more radio receivers. The purpose of these systems is to broadcast programs to the general public. However, the listener is not able to broadcast or send messages back to the station.

To better understand this form of communication, let us consider the block diagram of Figure 1. As shown, the radio system consists of two main parts. One part is the transmitter. At the transmitter, a microphone converts sound to electric signals. We refer to these signals as AUDIO SIGNALS. In the transmitter, the audio signal is combined with a radio wave commonly referred to as a CARRIER WAVE. This combined signal is radiated into space by an antenna.

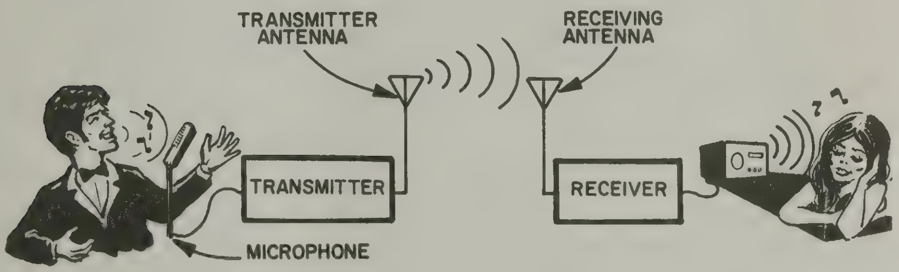


Figure 1

The second part of this radio system is the radio receiver. Here the combined carrier wave and audio signal is intercepted by the receiving antenna. The signal is fed into the radio receiver where the audio signal is removed from the combined wave. The audio signal is then amplified and converted to sound by the radio speaker.

You may have wondered how signals can pass from a transmitting antenna to a receiving antenna with no connecting wires between them. The answer is that the signal leaving the transmitting antenna is in the form of varying electric and magnetic fields. You will recall that an ordinary transformer transfers energy from its primary to its secondary in much the same way—the magnetic field around the primary cuts the secondary to induce a voltage.

You will also recall that one primary winding of a transformer may supply energy to more than one secondary winding. This holds true for radio transmitters and receivers as well. That is, one transmitting antenna often supplies energy to many receiving antennas.

To prevent radio interference between the different stations, definite carrier frequencies are assigned or allocated to every commercial broadcast transmitting station by the Federal Communications Commission (FCC). The FCC is an agency of the United States government which regulates all wire and radio communications between the states, territories and possessions. It does not include communications facilities operated by the federal government, such as military facilities.

THE RADIO SPECTRUM

The carrier frequencies allocated to the different radio systems are within a range of frequencies between 10 kilohertz (kilocycles) and 30,000 megahertz (megacycles). This range of frequencies is referred to as the **RADIO SPECTRUM.** Basically, there are seven frequency groups that make up the radio spectrum. These are shown in the chart of Figure 2. The first group covers a range of frequencies from 10 to 30 kHz. These are referred to as the Very Low Frequencies (VLF). They include the upper limit of the audio frequency range and the lower limit of the ultrasonic range.

DESIGNATION	ABBR	FREQUENCY
VERY LOW FREQUENCY	VLF	10 to 30 kHz
LOW FREQUENCY	LF	30 to 300 kHz
MEDIUM FREQUENCY	MF	300 to 3000 kHz
HIGH FREQUENCY	HF	3 to 30 MHz
VERY HIGH FREQUENCY	VHF	30 to 300 MHz
ULTRA HIGH FREQUENCY	UHF	300 to 3000 MHz
SUPER HIGH FREQUENCY	SHF	3000 to 30,000 MHz

Figure 2

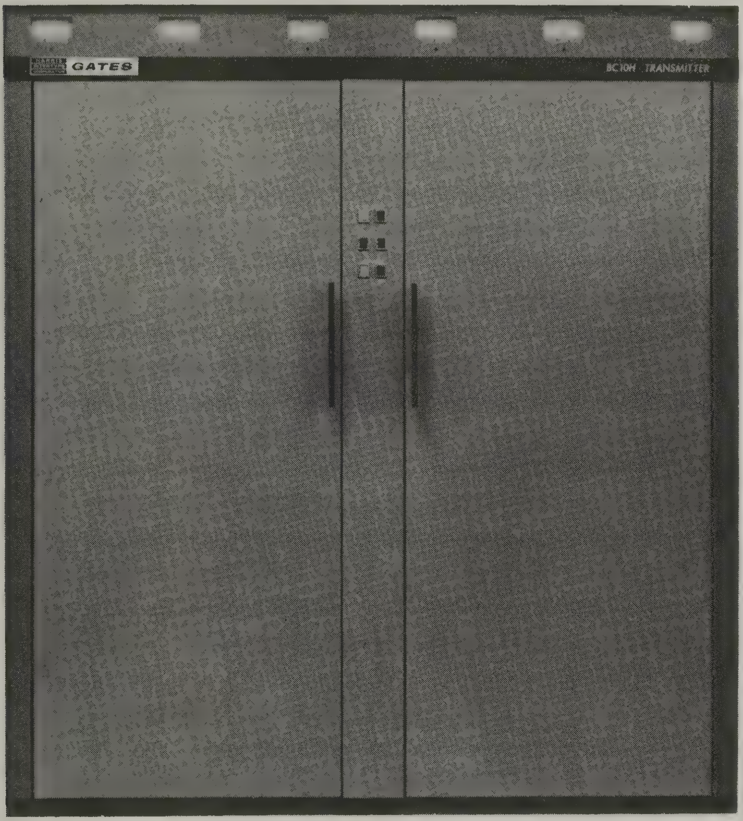
The next group is the Low Frequency range (LF), from 30 to 300 kHZ. These frequencies are for sea and air navigational aids. Medium Frequencies (MF), from 300 to 3000 kHZ, include sea and air radio navigation, amateur radio, fixed and mobile communications, and government radio, to name a few. Also included in this band of frequencies is the standard radio broadcast band (535 to 1605 kHz).

The range of frequencies from 3 to 30 MHz is referred to as High Frequencies (HF). This range of frequencies is used for therapeutic oscillators, commercial and amateur short wave communications and broadcasting, and electronic heating. The next range is the Very High Frequencies (VHF), from 30 to 300 MHz. These frequencies are used for television stations, FM broadcast stations, fixed and mobile radio systems, and for aeronautical and amateur radio systems.

Ultra High Frequencies (UHF) are next. They cover a range of frequencies from 300 to 3000 MHz. Some radio systems which use these frequencies are government, amateur, aeronautical, fixed and mobile radio. Also included is the UHF television band. From here we move into Super High Frequencies (SHF). These frequencies cover a range from 3000 to 30,000 MHz. Some users of this range are government, amateur, fixed and mobile radio, and radio navigation, to name a few.

Frequencies above 30,000 MHz are used for experimental, government and amateur use. The radio spectrum also includes the range of light energy.

Devices such as the laser can be used to transmit information by light energy. These devices are also used in satellite and space communications and eventually are expected to provide coast-to-coast and continent-to-continent communication links.



The above photo shows a 10-kW AM Transmitter designed for broadcast service.

Courtesy Gates Radio Co.
Div. of Harris Intertype Corp.

STANDARD BROADCAST STATIONS

Standard broadcast stations are licensed by the FCC for the transmission of intelligence primarily intended to be received by the general public. These stations operate in the band of frequencies from 535 kHz to 1605 kHz. Within the band of frequencies there are 107 carrier frequencies. These carrier frequencies are assigned to the various radio stations to convey intelligence from the transmitters to the radio receivers. The carrier frequencies are spaced 10 kilohertz apart. To prevent interference between one station and another, stations in the same area are not assigned adjacent carrier frequencies.

More than one station may be assigned to the same carrier frequency. This is done only when the FCC inspectors are certain that the two stations will not interfere with each other. For example, a station on the east coast may be assigned the same carrier frequency as a station on the west coast.

Two stations in the same area can also broadcast on the same frequency by sharing time. For example, one station may go on the air at sunrise and broadcast until sunset. The other station may broadcast at the same frequency from sunset until sunrise the next day.

Because several broadcast stations may operate at the same frequency, it becomes necessary to control the distribution of their radiated energy. One way to control the radiation is to use a DIRECTIONAL ANTENNA.

Directional antennas are used to direct the radio waves toward the center of highly populated areas. At the same time, they may be used to reduce the station radiated energy in other locations to prevent interference with other broadcast stations.

The amount of radio frequency power radiated by a broadcast station is also regulated by the FCC. Standard broadcast stations normally radiate between 100 watts and 50 kilowatts. The exact power depends on the type of license granted to the station by the FCC.

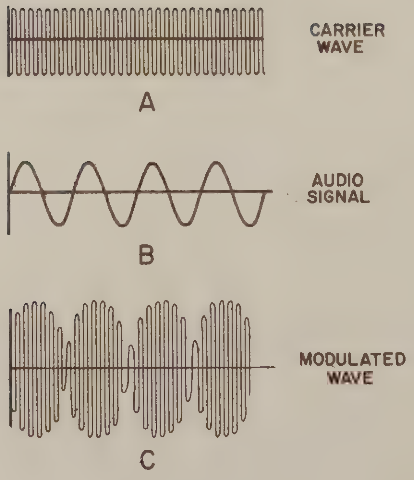


Figure 3

In standard broadcast systems, the energy radiated by the transmitting antenna is **AMPLITUDE MODULATED (AM).** By this we mean that the AMPLITUDE of the carrier wave is changed in accordance with the amplitude of the **MODULATING SIGNAL.** Figure 3 illustrates a carrier wave that is amplitude modulated by an audio signal. There are three waves to consider. They are the carrier wave, the audio wave or modulating signal, and the resulting modulated wave.

The high frequency carrier wave, shown in Figure 3A, is produced by an oscillator in the transmitter. The audio wave or signal, shown in Figure 3B, is the low frequency energy produced by the microphone. It is assumed to be within the audible range (about 16 to 20,000 hertz). This energy is used to modulate the carrier wave. When the audio wave and carrier wave are combined, the amplitude of the r-f carrier is varied in accordance with the audio wave as shown in Figure 3C.

Basic AM Transmitter

The block diagram of a basic AM transmitter is shown in Figure 4. The first step is to convert the sound energy to an audio frequency electric signal. This is accomplished by the microphone. The signal developed by the microphone, however, is very weak. Therefore, the audio signal is increased in magnitude by an audio amplifier to a level required to operate another amplifier called the **MODULATOR.** The modulator is the final audio amplifier and supplies the necessary audio power for modulation.

At the lower left of Figure 4, the radio frequency oscillator produces a high frequency ac output. The output of the r-f oscillator is applied to the **MODULATED STAGE.** In this stage, the signal from the output of the modulator stage produces amplitude changes in the carrier wave. The modulated wave is then fed to the antenna.

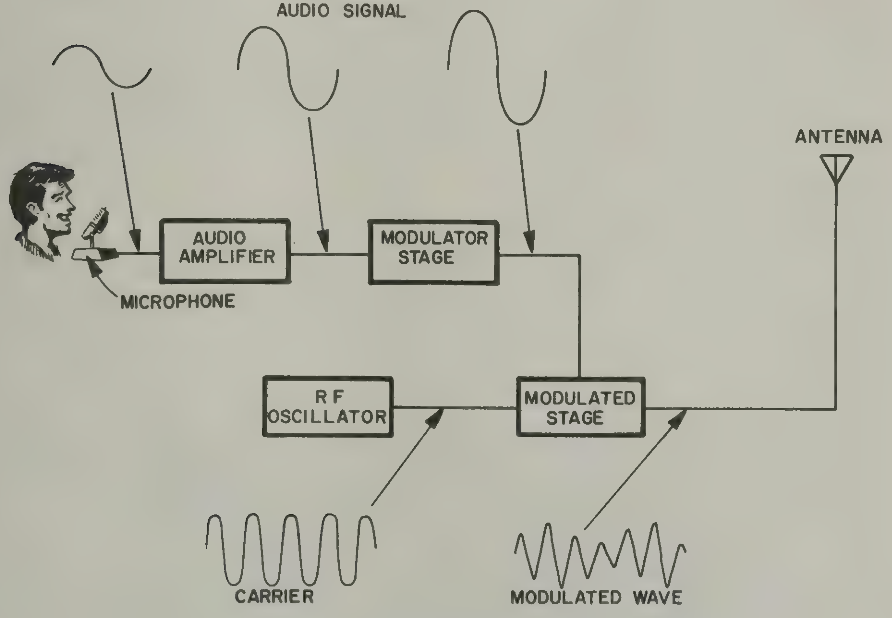


Figure 4

The energy radiated by a transmitting antenna consists of magnetic and electric fields. These fields are at right angles to each other. The relationship of the electric field with respect to the earth as the radio waves pass through space is referred to as polarization of the electric field.

For example, if the electric field is vertical with respect to the earth, the radio wave is said to be **VERTICALLY POLARIZED.** The type of polarization is determined by the construction of the transmitting antenna. Vertical polarization is the most common arrangement used in the standard AM broadcast band.

Basic AM Receiver

One of the most popular types of radio receivers in use today is the SUPERHETERODYNE RECEIVER. This is shown in the block diagram of Figure 5. As the magnetic field produced by the transmitting antenna cuts across the receiving antenna, a signal voltage appears between the ends of the receiving antenna. A modulated carrier waveform signal is shown at the antenna in Figure 5.

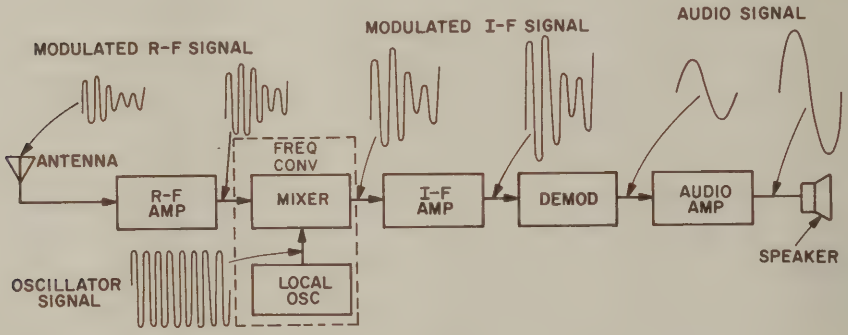


Figure 5

The energy of the antenna signal is very low, so the received signal voltages are fed into the r-f amplifier of the receiver. This stage increases the amplitude of the incoming modulated signal for further action by the receiver.

Many AM broadcast receivers do not use an r-f stage. They rely on amplification in the following stages to raise the signal to a usable level. However, receivers designed for long-range reception usually include one or more r-f amplifiers.

The input circuits of a receiver have the important job of picking out the one signal we want from the signals of all the other stations. This is the process of tuning. The input circuit can be tuned to resonance at a desired carrier frequency by varying the inductance or capacitance of an LC circuit. Signals at this resonant frequency are then passed on to the rest of the receiver. The unwanted frequencies are blocked by the resonant circuit and do not appear in the output.

The next receiver stage is the MIXER; it is used to combine the incoming r-f signal with an r-f signal from the LOCAL OSCILLATOR shown directly below it in Figure 5. The process of combining or mixing two different frequencies to produce a new frequency is called "beating" or "heterodyning." This is where the superheterodyne receiver gets its name. The FREQUENCY CONVERTER consists of the mixer and the local oscillator.

When the incoming r-f signal and the local oscillator signal are combined in the mixer, a new frequency called the **INTERMEDIATE FREQUENCY (I-F)** is produced. The intermediate frequency is the difference between the incoming carrier frequency and the local oscillator frequency. The i-f signal waveform is shown at the output of the mixer and i-f amplifier. Notice that the amplitude of this waveform varies according to the audio signal developed by the microphone at the transmitter. Thus, the i-f signal is also a modulated signal.

In the process of heterodyning we actually have four frequencies to consider. These are the carrier frequency, the local oscillator frequency, and the sum and difference of the two. The sum and difference frequencies result from the heterodyne action. In most receivers, the difference frequency signal is used. The others then have no further use and are removed by tuned circuits.

The local oscillator is adjusted so that its frequency always differs from the desired incoming r-f frequency by the same amount. Thus, the intermediate frequency is always the same, regardless of the setting of the tuning control. In most broadcast AM receivers, the i-f is 455 kHz. The oscillator

The modern music system shown above includes an FM/AM-FM Stereo Radio along with an 8-track stereo cartridge player.

Courtesy RCA

is adjusted so that its frequency is 455 kHz above the desired incoming r-f carrier. This frequency difference is maintained by using a multiple-section tuning capacitor which changes the oscillator frequency at the same time it changes the resonant frequency of the input circuits.

To illustrate this principle, suppose you want to pick up a station with a carrier frequency of 1000 kHz. As you tune the input circuit to 1000 kHz, the oscillator section of the tuning capacitor tunes the oscillator to 1455 kHz (455 kHz above the incoming signal). If you tune your receiver to pick up a station at 700 kHz, the oscillator is simultaneously tuned to 1155 kHz, which again is 455 kHz above the incoming carrier. The oscillator always operates 455 kHz above the incoming carrier, so that the output of the mixer or frequency converter is always 455 kHz.

You may think that this is a complicated way to design a radio. Actually, it would be possible to feed the r-f signal directly from the r-f amplifier to the demodulator stage. However, there are advantages to the superheterodyne system which make the added frequency conversion worthwhile. The most important advantage is that the i-f amplifier section can be designed to operate at a single frequency. It is easier to design and adjust an amplifier to work at a single frequency than to work over a wide range of frequencies.

The i-f signal is fed to the i-f amplifier. Here the i-f signal is increased in amplitude before it is fed into the **DEMODULATOR.** In the demodulator or **DETECTOR** stage, the i-f carrier is separated from the audio signal and discarded. As shown in Figure 5, the output of the demodulator is an audio signal equivalent to that of the original sound produced by the microphone at the transmitter. The audio signal is fed from the demodulator to an audio amplifier. Here the audio signal is increased in amplitude to operate the speaker.

FM BROADCAST SYSTEMS

Noise in AM reception results from electrical disturbances due to storms, automotive ignition systems, and many other energy sources. These disturbances amplitude modulate the carrier. Since an AM receiver is designed to detect amplitude modulation, the unwanted noise signals are detected and reproduced along with the desired signals. To overcome this noise problem, a system other than amplitude modulation can be used. For reasons that we shall explain, **FREQUENCY MODULATION (FM)** is one type of system that reduces the noise problem.

The following Practice Exercise questions cover the subjects which you have just studied. They are:

BROADCAST SYSTEMS

THE RADIO SPECTRUM

STANDARD BROADCAST STATIONS

BASIC AM TRANSMITTER

BASIC AM RECEIVER

1. What is a communication system?

2. What is a disadvantage of a direct voice communication system?

3. A limitation of telephone communications is that it requires the use of ________.

4. Name several types of intelligence transmitted by radio waves.

5. A radio broadcast station radiates audio signals directly into space. True or False?

6. What purpose does the FCC serve?

7. Standard broadcast stations in the United States operate in the Low Frequency range (30 to 300 kHz). True or False?

8. The carrier frequencies in the standard broadcast band are separated by (a) 10 kHz, (b) 100 kHz.

9. What is meant by the term "amplitude modulation?"

10. The radio frequency energy radiated by stations in the standard AM broadcast band is ______________ polarized.

11. What is the most popular type of AM radio receiver in use today?

12. In a radio receiver, when you tune from one station to another, what change occurs in the tuning circuits?

13. The purpose of the converter or mixer stage of a superheterodyne receiver is to convert the incoming r-f signal to the desired (a) audio signal, (b) i-f signal.

14. The purpose of the demodulator of a superheterodyne receiver is to change the i-f signal to a radio frequency signal. True or False?

Frequency modulation is used to broadcast radio programs like that of AM broadcast stations. It is also used for the transmission of the sound portion of television programs and is widely used in government and civilian communications. In the United States, FM broadcast stations are located in the frequency spectrum from 88 to 108 megahertz. There are a total of 100 channels set aside in this band.

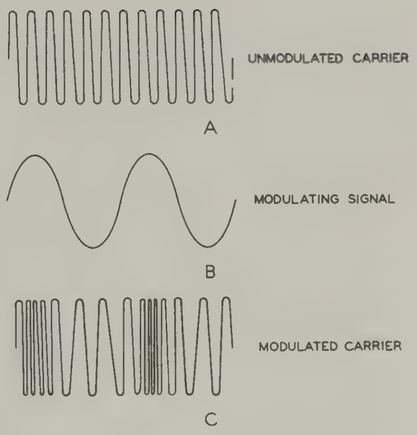


Figure 6

In frequency modulation, the FREQUENCY of the carrier is varied by the amplitude of the modulating signal. Thus, the intelligence is transmitted in the form of frequency variations, compared to the amplitude variations in an AM system.

Figure 6 illustrates the frequency modulation principle. Figure 6A shows the unmodulated carrier of an FM transmitter. The frequency of this carrier is referred to as the CENTER FREQUENCY. This corresponds to the assigned frequency of the transmitter.

Figure 6B shows an audio or low frequency modulating signal. When this signal modulates the carrier, we obtain the resulting waveform shown in Figure 6C. Notice that the frequency of the modulated wave varies according to the audio modulating signal. The amplitude of the carrier does not change.

A modulated FM wave is continually varying in frequency. The amount of variation above and below the center frequency is called **DEVIATION**. The maximum deviation allowed for commercial FM broadcast is ±75 kHz. That is, the strongest signal that can be used to modulate a transmitter is limited to the value which will cause a maximum deviation of 75 kHz on either side of the center frequency. This is called the maximum FREQUENCY SWING. Thus, a total of 150 kHz is available over which the frequency of any one station may vary.

A band of 25 kHz at each end of the channel is also provided for separation purposes between channels. This 25 kHz band is called the **GUARD BAND**. Thus, a standard FM broadcast channel consists of a center frequency with a maximum frequency deviation of ±75 kHz, plus a 25 kHz guard band on either side, for a total of 200 kHz per channel.

Basic FM Transmitter

The basic elements of a simple FM transmitter are shown in Figure 7. The microphone converts the sound into an audio signal. The audio signal is strengthened by the audio amplifiers. This signal is then applied to the oscillator stage where it varies the frequency of the oscillator. The last block in Figure 7 is the high frequency power amplifier. It increases the power of the modulated wave to the level required for transmission. The output of the power amplifier is fed to the antenna.

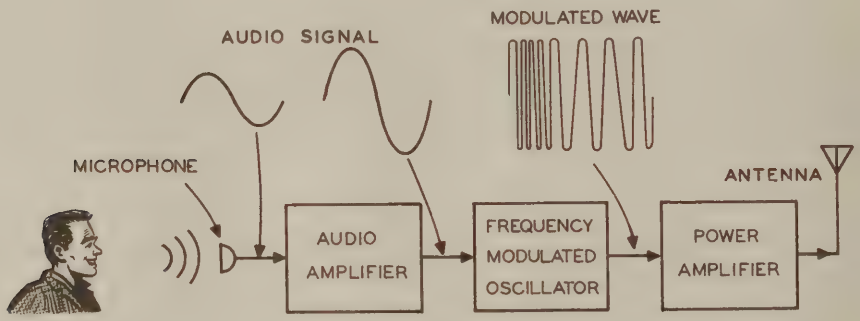


Figure 7

Antennas used by FM broadcast transmitters are normally **HORIZONTALLY POLARIZED.** Some stations employ both horizontal and vertical polarization. The electric fields of the radio waves are horizontal with respect to the earth. For maximum signal pickup, the receiving antenna elements should also be horizontally polarized. This occurs when the elements of the receiving antenna are horizontal with respect to the earth.

It should be mentioned here that the method of modulation does not determine the polarization of the signal. It is the physical construction of the transmitting antenna that determines the polarization of the radio wave.

Basic FM Receiver

The basic stages of an FM superheterodyne receiver are shown in the block diagram of Figure 8. The first four stages are similar to those of an AM superheterodyne receiver. That is, signal voltages are fed into the r-f amplifier from the antenna. The output signal of this stage is fed into the mixer. The mixer, along with the local oscillator stage, produces the required intermediate frequency. In the case of an FM broadcast receiver the i-f frequency is usually 10.7 MHz. This signal is increased in amplitude by the i-f amplifier. More than one i-f amplifier may be used.

The circuit of Figure 8 includes a **LIMITER.** The limiter is used to clip off or remove any amplitude variations in the FM signal. Since the intelligence

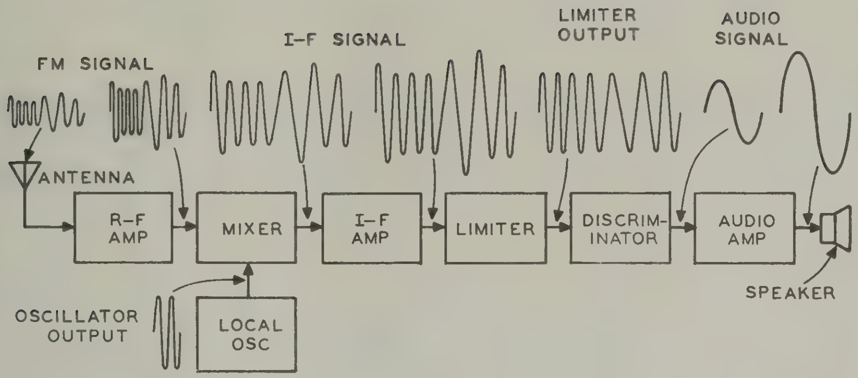


Figure 8

is in the form of frequency variations, any amplitude variations that may be present must be unwanted amplitude modulation due to electrical interference. By removing such variations we remove noise from the speaker output and also help provide a more constant level of output. As explained earlier, this noise limiting ability is an important advantage of FM over AM.

The limiter output is fed to the **DISCRIMINATOR.** The discriminator recovers the audio signal produced by the microphone at the transmitter. The discriminator is, therefore, an FM detector or demodulator. Following the discriminator is an audio amplifier which increases the audio signal to a level sufficient to operate the speaker. There are other types of detectors for FM signals; some of these detectors do not require limiters.

This SSB transceiver is designed for Amateur Radio Service in the 6 meter band (50-54 MHz).
Courtesy Heath Co.

TV BROADCASTING SYSTEMS

Television broadcasting requires the transmission of both sound and picture intelligence by means of radio waves traveling through space. The FCC has assigned parts of the VHF and UHF spectrums to be used for television broadcasting.

There are a total of 82 television channels. These channel assignments are broken down in the following manner. Channels 2 through 6 cover a range of frequencies from 54 to 88 MHz. These are referred to as the "low band" VHF stations. Channels 7 through 13 cover a range of frequencies from 174 to 216 MHz. These are referred to as the "high band" VHF stations. Channels 14 through 83 cover a range of frequencies from 470 to 890 MHz and are called UHF stations.

The maximum effective radiated powers (ERP) assigned to the various TV broadcast stations are 100 kW for Channels 2 through 6, 316 kW for Channels 7 through 13 and 5000 kW for Channels 14 through 83. Channel 1 is no longer used for television broadcasting since it has been reallocated to other communication services.

The bandwidth of each channel is 6 MHz. Within this band of frequencies there is a picture carrier, sound carrier, and for color transmissions, a color subcarrier.

The FCC specifies that the video carrier (picture carrier) be located 1.25 MHz higher in frequency than the lower limit of the channel. The FCC also specifies that the video carrier be amplitude modulated as in AM transmission. The sound carrier, however, is frequency modulated and is 4.5 MHz higher in frequency than the video carrier. The color subcarrier is used for the transmission of the color intelligence. The color subcarrier is about 3.58 MHz from the video carrier and is amplitude modulated.

The basic elements that make up a typical television transmitting system are shown in Figure 9. The television station is different from the radio station in that television stations use two transmitters. One transmitter is used for transmitting the picture intelligence and the other for the sound intelligence. However, at the receiver location, both transmitted signals are picked up by a single antenna and fed to a single receiver.

As shown in Figure 9, light reflected by the object or scene being televised is picked up by a camera tube. The camera tube, in turn, changes the light

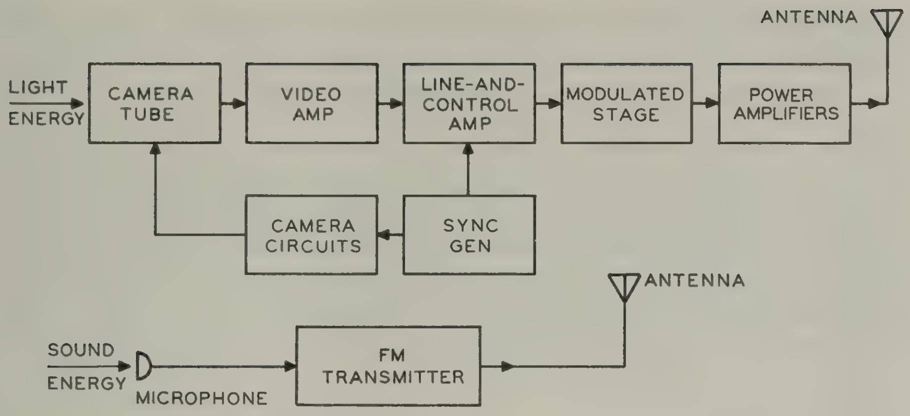


Figure 9

variations into voltage variations. We refer to these voltage changes as the **VIDEO SIGNAL.**

Because the video signal at the output of the camera tube is very weak, it must be amplified before it can be of any use. This is accomplished by the video amplifier. The output from the video amplifier is fed into another amplifier called the LINE-AND-CONTROL AMPLIFIER. Here the video signal is combined with two other signals that are necessary for the transmission of the television signal. These signals are called the **SYNCHRONIZING PULSES** and **BLANKING PULSES.**

Synchronizing and blanking pulses are produced in the SYNC GENERATOR. The purpose of these pulses is to synchronize, or keep in step, the entire television system. In the camera circuits they control the scanning action of the camera tube. At the receiver they control the scanning action of the picture tube, thus keeping it in step with the camera tube.

The output of the control amplifier is fed into the modulated stage. Here, the video signal amplitude modulates an r-f carrier. This modulated signal is fed to the power amplifier and then to the antenna for radiation into space.

The sound transmitter is a frequency modulated system much like the FM transmitter described for FM broadcasting. Figure 9 shows two separate antennas—one for the video section (AM) and the other for the audio section (FM). Although this system can be used, most stations use a single antenna to radiate both the video and audio signals. A special section called a DIPLEXER then feeds the outputs of the two transmitters to the single antenna.

Figure 10 shows a typical television receiver in block diagram form. This is a superheterodyne circuit which has an r-f amplifier, mixer and oscillator similar to those found in AM and FM broadcast receivers. The i-f amplifier usually consists of several stages of amplification. The video detector is similar to an AM broadcast detector but it has several outputs. These include a picture signal, blanking pulses, sync signals and the 4.5-MHz sound carrier which is frequency modulated.

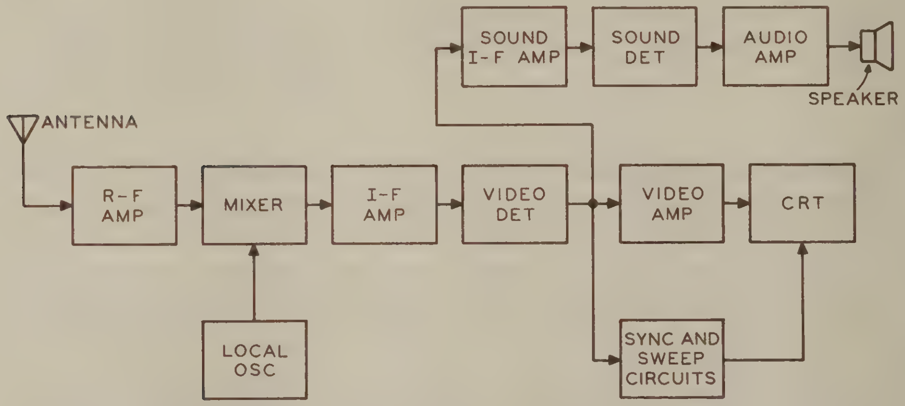


Figure 10

The picture information and blanking pulses pass through the video amplifier to either the control grid or cathode of the picture tube. The sync pulses are fed to sync and sweep circuits. The signals fed to these circuits determine the movement of the electron beam across the screen of the picture tube. The picture tube screen fluoresces or forms light images according to the intensity of the electron beam striking it.

The 4.5 MHz i-f output produced by the video detector carries the sound or audio signal as frequency modulation. This output is fed to a 4.5 MHz i-f amplifier and then to an FM detector similar to that used in an FM broadcast receiver. The detector output is an audio frequency signal which is amplified and fed to a speaker.

RADIO TELEMETRY SYSTEMS

We usually think of communications as the transmission of voice or music, or in the case of television, as the transmission of pictures. However, another important type of communication is the transmission of information on measurements from the point of measurement to some other point. This type of communication is called **TELEMETRY.**

A radio telemetry system is one that uses an r-f carrier to transmit measurements from a remote location to a more convenient location. For example, a weather balloon carrying a miniature transmitter sends out signals which depend on variations of pressure, humidity or temperature. These variations are relayed to a ground receiver by means of an r-f carrier generated in the transmitter. The receiver, in turn, converts the information back to a form to be recorded.

Radio telemetry is also used in recording data of a missile, rocket or airplane under test. For example, it allows the technician on the ground to see how the structural members of the craft are holding up under flight. It also may tell him the temperature of the metal on the outside of the craft. Or it may tell him the amount of fuel left, or at what angle the craft is with respect to earth.

There are a number of frequencies allocated for radio telemetry use. Some of the frequencies are 216 to 220 MHz, 1435 to 1535 MHz, and 2200 to 2300 MHz. The maximum r-f carrier deviation in these bands is ±125 kHz for a total swing of 250 kHz. For frequencies between 216 to 220 MHz the maximum power that may be used is 100 watts. For frequencies between 1435 to 1535 MHz and 2200 to 2300 MHz, the maximum power depends on the transmission distance and any propagation problems that may exist. No more power should be used than is necessary for reliable transmission.

In the field of radio telemetry it is often necessary to transmit more than one channel of information. This can be accomplished by **MULTIPLEXING.** Multiplexing is the transmission of more than one type of information using a single transmitter. There are two general methods of multiplexing. They are: FREQUENCY DIVISION and TIME DIVISION.

In a frequency division multiplexing system, a number of low-frequency subcarriers are modulated—each with a different type of information. These subcarriers are then combined into a single electric signal that modulates the main r-f carrier.

Figure 11 illustrates the method used in frequency division multiplexing. Subcarrier oscillators 1 and 2 generate subcarriers at different frequencies. Signal 1 modulates the output of subcarrier oscillator 1, and signal 2 modulates the output of subcarrier 2. The modulated subcarriers are combined in a linear mixer. The mixing process here is simply a matter of combining the two modulated subcarriers so that the output of the mixer contains both signals.

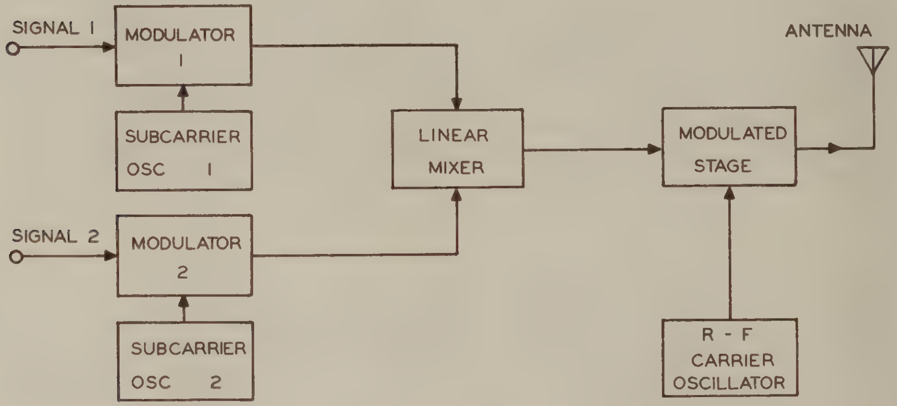


Figure 11

The mixer output is fed to the modulated stage, where it modulates the carrier generated by the r-f carrier oscillator. The r-f wave radiated by the antenna is a carrier modulated by the two distinct signals applied to inputs 1 and 2. To illustrate an application, signal 1 might be information on temperature, and signal 2 might be information on pressure. Both signals could be demodulated and separated by a properly designed receiver, and used to operate temperature and pressure indicators at a receiving station. The number of signals can be increased by adding more subcarrier channels.

In time division multiplexing, the signals to be transmitted are impressed on a single carrier at different times. Figure 12 shows a simple diagram of how this can be done. The multiplexing element here is a mechanically driven switch called a COMMUTATOR. As the arm rotates, it alternately makes contact with the shaded contact and the unshaded contact. Depending on which contact the arm is touching at a given time, either signal 1 or signal 2 is applied to the modulator.

The r-f oscillator generates a carrier which is modulated by signal 1 for half of the time, and by signal 2 for the other half of the time. The switching time depends on the speed of the motor that drives the commutator arm. To handle a greater number of signals, we simply break the commutator up into more sections.

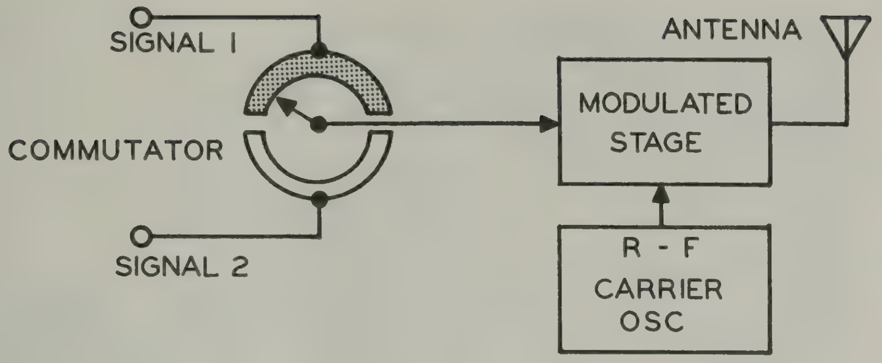


Figure 12

When a multiplexed signal is demodulated at the receiver, the different signals must be separated before they can be fed to the various indicators or recording devices. A DEMULTIPLEXER is used for this purpose. In a frequency division system, the demultiplexer consists of bandpass filters tuned to the various subcarrier frequencies. After the modulated subcarriers are separated by the filter action, they are demodulated to restore the original signals.

In a time division system, the demultiplexer is a commutator in reverse, or what is called a DECOMMUTATOR. The demodulated signal is fed to the rotating arm, and the indicators or recorders are connected to fixed contacts identical to the shaded and unshaded contacts of Figure 12. The commutator and decommutator must be synchronized so that the arm is on the signal 1 contact of the decommutator at exactly the same time it is on the signal 1 contact of the commutator.

Amplitude or frequency modulation can be used in radio telemetry systems. In a time division system, such as that of Figure 12, the carrier may be either amplitude modulated or frequency modulated by the signals from the commutator. In a frequency division system such as that of Figure 11, we also have a choice of how to modulate the subcarriers.

A special type of notation is used to indicate the method of multiplexing and modulation in a frequency division system. The subcarrier modulation is listed first, and the main carrier modulation is listed second. For example, AM-FM means the subcarriers are amplitude modulated by the input signals, and the subcarriers are then used to frequency modulate the r-f carrier of the transmitter.

Most mobile radio units used in public safety service and industrial applications employ FM. The unit shown above has a power rating of 50 watts and is designed to operate in the 25-54 MHz band.

Courtesy Aerotron Inc.

TWO-WAY COMMUNICATION SYSTEMS

The communications systems so far discussed in this lesson have all been of the one-way type. Two-way systems are also very widely used. A two-way system provides communication back and forth between two locations. A telephone conversation between two people is an example of two-way communication. Wireless or radio two-way systems are used to increase the effectiveness of many businesses and organizations.

For example, two-way radio is used to communicate from one aircraft to another. It is also used to communicate from an aircraft to the control tower and from the control tower to the aircraft. It may also be used between a mobile unit such as a taxi cab and a dispatcher. In addition, two-way radio provides communication between ships at sea and between ships and shore stations.

Two-way communication can be divided into seven general classes of service. These are Marine, Aeronautical, Public Safety, Industrial, Land Transportation, Personal and Disaster communications.

The following Practice Exercise questions cover the subjects which you have just studied. They are:

FM BROADCAST SYSTEMS

BASIC FM TRANSMITTER

BASIC FM RECEIVER

TV BROADCASTING SYSTEMS

RADIO TELEMETRY SYSTEMS

15. Name one advantage of a frequency modulation system.

16. What range of frequencies is allocated for FM broadcast stations in the United States?

17. What is the maximum frequency deviation of the carrier of an FM broadcast system?

18. The radio frequency energy transmitted by a station in the FM broadcast band is ____________________ polarized.

19. The polarization of the transmitted r-f signal is determined by (a) the method of modulation, (b) the physical construction of the transmitting antenna.

20. Why is an FM system normally less susceptible to noise than an AM system?

21. Television broadcasting is limited to the VHF band. True or False?

22. The high band VHF TV channels are in the frequency range from (a) 54 to 88 MHz, (b) 174 to 216 MHz, (c) 470 to 890 MHz.

23. What is the bandwidth assigned for each TV channel?

24. The FCC standards state that the video r-f carrier in a TV broadcast shall be (a) amplitude modulated, (b) frequency modulated.

25. The sound carrier of a TV broadcast is (a) amplitude modulated, (b) frequency modulated.

26. What is the frequency separation between the picture carrier and sound carrier in a TV broadcast signal?

27. What is the purpose of the sync and blanking pulses generated in a TV transmitter?

28. The video and audio sections of a TV transmitting station can be compared to an AM and FM broadcast station, respectively. True or False?

29. What is a telemetry system?

30. A radio telemetry system is one which uses an r-f carrier to transmit information. True or False?

31. What portions of the frequency spectrum are allocated to radio telemetry systems?

32. In radio telemetry, the maximum permissible deviation of the r-f carrier is ±250 kHz. True or False?

33. What is the purpose of multiplexing in telemetry systems?

34. One method of multiplexing uses subcarrier signals at different frequencies. This multiplexing method is called (a) frequency division multiplexing, (b) time division multiplexing.

35. Another method of multiplexing modulates the carrier with different signals at different times. This multiplexing method is called (a) frequency division multiplexing, (b) time division multiplexing.

Marine or Maritime services cover communications between ship to ship and ship to shore, as well as navigational aids. All stations on board ships of U.S. registry (except for government stations) are required to be licensed by the FCC and to comply with all FCC rules and regulations.

Aeronautical services cover both traffic control and navigational aids. These services offer the necessary communications facilities to provide protection of life and property in the air. Aircraft stations are those stations installed aboard aircraft. Aeronautical stations are those listed as ground stations.

There are several different types of stations which aid Public Safety. These stations are assigned to agencies concerned with the public welfare. Such stations include police, fire, forestry conservation, highway maintenance and special emergency operations.

Industrial services provide two-way communications for such groups as gas and electrical utilities companies, petroleum companies maintaining pipe lines, and groups working in the production of forestry products.

Land Transportation services involve companies that operate taxi cabs, railroads, highway trucks and automobile emergency services. A trucking company, for example, may use two-way radio to communicate with a truck driver on the highway to inform him of an unscheduled pickup or delivery. The truck driver in turn can use his radio to notify his company of a breakdown or accident.

Personal service covers the Amateur Radio Service which gives interested persons opportunities to engage in radio communications and experimentation as a hobby. Also covered is the Citizens Radio Service. This is a radio communication service of fixed, land and mobile stations intended for use by citizens of the United States for private or personal radio communications. This also includes radio control equipment such as radio controlled gates, garage doors, airplanes and boats, to name but a few.

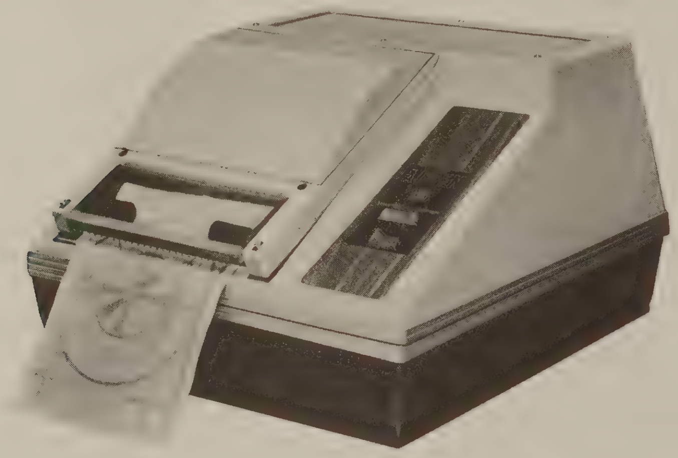
Disaster service provides the necessary communications in time of disaster or other incidents which involve disruption of regular communications facilities. When there is no disaster, or threat of one, these stations may communicate only with respect to drills and practice sessions and to conduct equipment tests. In time of emergency or disaster, they carry any communications necessary to relief work, including personal matters.

Frequency Allocations

The services so far discussed use various frequencies in the radio frequency spectrum. Public Safety, Industrial, and Land Transportation services are located in the band of frequencies from 25 to 50 MHz, 150 to 174 MHz and 450 to 470 MHz. Marine and Aeronautical services are also allocated at different points along the spectrum. Some of the bands allocated to their services are from 3.15 to 3.20 MHz, 0.2 to .285 MHz, or from .325 to .415 MHz, depending upon their use.

Citizen radio services are allocated from 26.9 to 27.2 MHz and 462.5 to 466.4 MHz. Amateur radio services, on the other hand, occupy a number of points along the frequency spectrum. Some of the amateur bands are 3500 to 4000 kHz, 7000 to 7300 kHz and 144 to 148 MHz. Disaster communication systems operate from 1750 to 1800 kHz.

The bandwidth assigned to two-way systems may be as little as 6 kHz or as much as 50 kHz. Two-way communications systems can be either amplitude modulated or frequency modulated. Frequency modulation is the most popular type at present.



The facsimile unit shown above is designed to produce "hard copy" from a television signal.
Courtesy Alden Electronic and Impulse Recording Equipment Co., Inc.

TWO-WAY COMMUNICATION EQUIPMENT

A complete two-way communication system generally must have at least two transmitters and two receivers. These may operate on the same or different frequencies. If they are on the same frequency, the transmissions must alternate. That is, to avoid interference, one transmitter must be off while the other is on. Some systems use **TRANSCEIVERS**, which have a transmitter and receiver built into the same unit. Some of the circuits may be shared by the transmitter and receiver sections. This is done by switches which change from "transmit" to "receive" operation.

Most communications receivers use a superheterodyne circuit. In general, a communications receiver has more stages than the average broadcast receiver. This provides greater SENSITIVITY (the ability to receive weaker signals), and SELECTIVITY (the ability to distinguish between signals separated by only a small frequency difference). They may have more than one r-f amplifier stage and several i-f amplifier stages. The circuits are also built to be very stable. By this we mean that they will remain tuned to a station regardless of supply voltage changes, mechanical vibrations, temperature changes, or other factors which could influence tuning.

There are also some special circuits which appear in communications receivers. One of the signals a communications receiver may have to receive is a continuous wave (CW) signal used to transmit Morse Code. The CW signal is an r-f carrier without any modulation. The r-f carrier is simply turned on and off by a telegraph key to produce a series of dots and dashes. Since the carrier is unmodulated, the detector in a broadcast receiver produces no output when a CW signal is received.

The AM receiver of Figure 13 includes a circuit to produce an output tone when an unmodulated or CW carrier is received. A special oscillator, called a BEAT FREQUENCY OSCILLATOR (BFO), is added to this circuit. This oscillator is tuned to a frequency about 1 kHz different from the intermediate frequency. When an unmodulated carrier is received, it is mixed in the second detector with the signal from the BFO. Because the i-f amplifier output is 1 kHz from the BFO output, a 1-kHz difference frequency is produced. This frequency is audible when applied to a speaker.

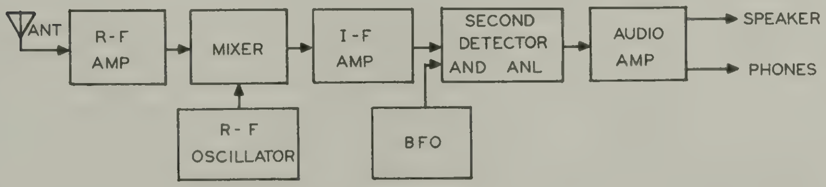


Figure 13

Thus, in the receiver of Figure 13, a 1-kHz audio note is produced whenever a dot or dash arrives. Since the BFO would produce a disturbing 1-kHz note for voice or music broadcast, a special switch on the front panel enables us to turn the BFO on and off as desired.

The receiver of Figure 13 also has an automatic noise limiter (ANL) as a part of the second detector. This system automatically limits the detector output if static causes a sudden burst of energy. While such limiters produce some distortion, they are used quite often for voice reception.

FACSIMILE SYSTEMS

Perhaps one of the least known communications systems, yet one of the most useful, is the **FACSIMILE SYSTEM.** Facsimile is a communication system for the transmission of fixed images for reception in permanent form. By facsimile we are able to transmit and receive fixed images over electric wires or by r-f carrier between distant points. These fixed images may be pictures, weather maps or typewritten or printed texts, to name just a few.

Figure 14 shows a basic facsimile transmitter. The picture, or other information to be transmitted, is wrapped around a cylinder. The cylinder is then rotated at a constant speed. As it rotates, it is moved back and forth along the shaft on which the drum is mounted. A strong light source is directed toward the revolving drum through a condenser lens and aperture. This beam is concentrated by the focus lens to illuminate a very small scanning area of the copy. Through a suitable pickup lens, the reflected light is then directed to the cathode of a photoelectric cell.

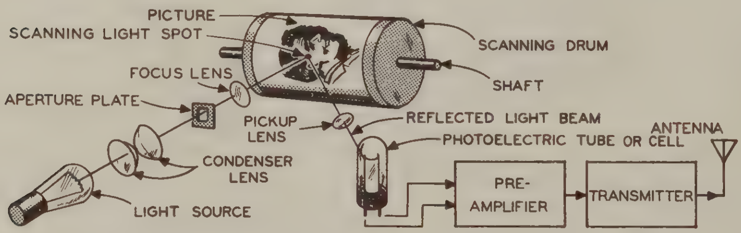


Figure 14

As the drum turns, the scanning spot reflects light in proportion to the density (darkness or lightness) of the illuminated area of the copy. These variations of reflected light cause the photoelectric cell to generate corresponding electric pulses. These pulses are applied to the input of a preamplifier, which feeds a transmitter.

At the receiver, a recorder converts the signal variations to a reproduction of the picture being transmitted. This reproduction can be made in any one of several ways.

One method of recording facsimile information is shown in Figure 15. A sheet of light-sensitive paper is wrapped around a drum. This paper is scanned by a small spot of light. The brilliance of this light depends on the received signal. This light exposes the film. The recorder drum rotates and moves in step with the transmitter drum. After exposure, the light sensitive paper is developed by the usual photographic methods.

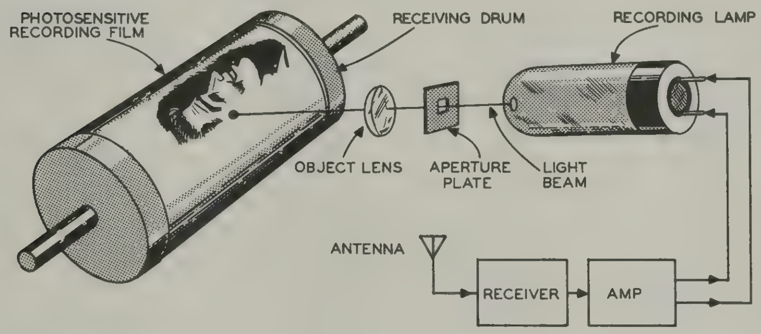


Figure 15

Like other radio communications systems, facsimile is also governed by a set of standards set forth by the FCC.

In a facsimile system that amplitude modulates a carrier, the maximum density or blackness of the subject copy generally corresponds to the maximum carrier amplitude. In a facsimile system that frequency modulates a carrier, the highest transmitted frequency generally corresponds to the maximum blackness of the subject copy. These systems, known as negative modulation, are illustrated in Figure 16.

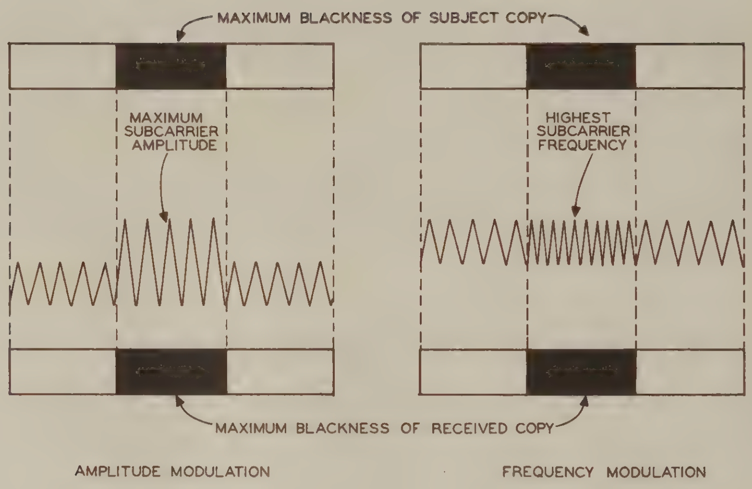

MAXIMUM BLACKNESS OF SUBJECT COPY
MAXIMUM SUBCARRIER AMPLITUDE
HIGHEST SUBCARRIER FREQUENCY
MAXIMUM BLACKNESS OF RECEIVED COPY
AMPLITUDE MODULATION
FREQUENCY MODULATION

Figure 16

Facsimile may be found in newspaper offices, police stations, weather bureaus and telegraph offices, to name a few. In many instances, facsimile is not sent by an r-f carrier wave. Instead, a direct wire much like the telephone is employed.

RADAR SYSTEMS

The word **RADAR** is derived from the phrase RAdio Detection And Ranging. Radar systems enable us to use radio waves to determine the direction and distance of an object from a transmitting station.

In a radar system, high power r-f energy, usually in the range of 1000 MHz to 30,000 MHz, is transmitted from a directional antenna in a narrow beam. When the r-f energy strikes an object in the beam path, a small amount of the energy is reflected back to the same antenna or to a separate receiving antenna. Thus, the principle is very much like that of an echo returning to the source of sound.

A receiver detects the reflected energy and compares it with a sample of the original transmission to determine certain facts about the object, such as its direction and distance.

To better understand the basic radar system, it is important to study the various stages which make up the system, as shown in Figure 17. This system is divided into six blocks; the pulse timer, the pulse modulator, the transmitter, transmit-receive (T-R) switch, receiver and crt indicator.

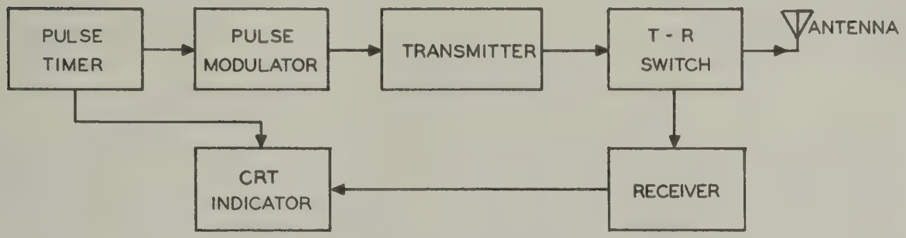


Figure 17

The pulse timer produces pulses at a fixed rate. These pulses are applied to both the pulse modulator and crt indicator. This synchronizes both ends of the system. The pulse modulator accepts the timing pulses and shapes and amplifies the pulses. These pulses are then used to key the transmitter oscillator at the desired rate and for the proper time duration.

Thus, the transmitter produces short bursts of r-f carrier energy at regularly spaced intervals. This particular system uses the same antenna for transmitting and receiving. The energy bursts are applied to the antenna, through the T-R switch, for radiation into space. When the radar transmitter is sending out a pulse of r-f energy, the T-R switch connects the transmitter to the antenna. During the intervals that the transmitter is off, the T-R switch connects the receiver to the antenna to pick up the echo. The antenna is highly directive and concentrates the transmitted r-f energy into a narrow beam.

The same antenna receives the minute energy or echo reflected from any object in the path of the transmitted beam. This received signal reaches the receiver through the T-R switch. In the receiver, the r-f signal is converted to an i-f signal, demodulated and amplified. The output of the receiver is then applied to the cathode ray tube for a visual presentation.

In the simplest radar system, the time between transmission and reception is shown by two peaks or pips rising up from a straight horizontal line. One pip is produced at the instant the signal is transmitted. The other pip is produced when the echo returns. The distance between the two pips depends on the time between transmission and reception, which in turn depends on the distance to the reflecting object. If a scale calibrated in miles, yards or feet is attached to the crt, the distance can be read directly from the screen.

Since the energy is transmitted in a highly directional beam, the direction of the object is determined by the direction in which the antenna faces at the time of the transmission.

SUMMARY

One-way and two-way communications systems convey information over long distances. Standard AM broadcast radio is one method used to convey information by one-way transmission. The AM broadcast band includes frequencies from 535 to 1605 kHz. This type of communication is used to convey news and entertainment to the general public.

FM broadcasting provides another means of one-way communications. This system operates in the radio frequency spectrum from 88 to 108 MHz, and the carrier is frequency modulated. This type of modulation eliminates many interference problems encountered in AM radio.

Television broadcasting, also a one-way system, is the transmission and reception of sound and picture intelligence by means of radio waves traveling through space. Television operates in a range of frequencies from 54 to 88 MHz, 174 to 216 MHz, and from 470 to 890 MHz. The picture intelligence amplitude modulates the picture carrier, whereas the sound intelligence frequency modulates the sound carrier.

Radio telemetry systems enable us to make measurements at remote locations. An r-f carrier wave is used to transmit this information. These measurements are then received, demodulated and reproduced at a more convenient location. Radio telemetry also uses multiplexing which allows us to transmit more bits of information using a single transmitter. Two types of multiplexing used in telemetry are time division and frequency division.

Two-way communication differs from broadcast communication in that we are able to communicate back and forth between two points. Two-way systems use a number of frequencies depending on the use of the system. Some uses are in the areas of aeronautical, public safety, industrial radio, land transportation, marine, personal and disaster services.

Another useful communication device is the facsimile system. This system allows us to transmit and receive fixed images by means of wires or an r-f carrier wave. Facsimile is transmitted through the air using frequencies between 88 and 108 MHz. This is made possible by transmitting facsimile during the time that the regular FM broadcasting is signed off the air. An-

The following Practice Exercise questions cover the subjects which you have just studied. They are:

TWO-WAY COMMUNICATION SYSTEMS

FREQUENCY ALLOCATIONS

TWO-WAY COMMUNICATION EQUIPMENT

FACSIMILE SYSTEMS

RADAR SYSTEMS

36. What are the seven general classes of services that use two-way communications?

37. Two bands in the frequency spectrum that are widely used for land, public and industrial two-way systems are 152 to 174 MHz and 450-470 MHz. True or False?

38. The bandwidth of a two-way communication transmitter is usually between (a) 6 to 50 kHz, (b) 60 to 500 kHz.

39. The type of modulation which is most popular in two-way communication is (a) amplitude modulation, (b) frequency modulation.

40. Why is a BFO required for reception of CW signals?

41. Noise due to static can be reduced in a communications receiver by (a) a BFO, (b) an automatic noise limiter.

42. A facsimile system is one which permits the transmission of fixed images so they can be received and reproduced in permanent form. True or False?

43. What type of data can be sent over a facsimile system?

44. In a facsimile receiver, the permanent reproduction is formed by a photocell. True or False?

45. The purpose of a radar system is to determine the direction and distance of an object. True or False?

46. What range of frequencies is used for radar systems?

47. In a radar system, the distance of an object can be determined from the direction in which the antenna faces at the time the energy is transmitted. True or False?

other method is the transmission of facsimile along with the regular FM broadcast by multiplexing.

Radar systems are used to detect and determine the direction and distance of objects from a radar transmitter. A radar station consisting of a transmitter and receiver may be located on land, aboard ship or aboard an airplane. Radar systems operate in a range of frequencies from 1000 to 30,000 MHz.

Basically, the radar transmitter sends out a strong burst, or pulse, of r-f carrier energy using a highly directional antenna. Any object in the path of this r-f energy will reflect a small amount of the energy back to the radar antenna. This small amount of energy is detected by the same antenna or by a separate receiving antenna, and is then fed into a receiver. At the receiver, the returned pulse is compared with that of a transmitted pulse to determine the distance of the object from the radar station.

IMPORTANT DEFINITIONS

AMPLITUDE MODULATION (AM)—A type of modulation in which the amplitude of the carrier varies in accordance with the modulating signal.

BLANKING PULSE—A pulse used to cut off the electron beam in television camera and picture tubes during the time when no picture is being formed.

DEMODULATOR—A circuit or a stage of a radio receiver used to recover the modulating signal from a modulated carrier. Also called a DETECTOR.

DETECTOR—See DEMODULATOR.

DEVIATION—In an FM system, the amount an r-f carrier is varied above and below its center frequency. Also called FREQUENCY DEVIATION.

DISCRIMINATOR—The detector circuit or stage of an FM receiver that converts frequency modulated signals into audio signals.

FACSIMILE SYSTEM—A system used to transmit and receive fixed images, such as photographs, weather maps, and typewritten matter, between widely separated points by use of r-f carrier waves or electric wires.

FREQUENCY MODULATION (FM)—A type of modulation in which the frequency of the carrier varies in accordance with the modulating signal.

GUARD BAND—A narrow band of frequencies provided between adjacent carriers in certain portions of the spectrum to prevent interference between stations.

HORIZONTALLY POLARIZED—Transmission of radio waves in such a way that the electric field of the wave is horizontal (parallel to the earth's surface).

INTELLIGENCE—The information conveyed by radio waves in communications systems.

INTERMEDIATE FREQUENCY (I-F)—The difference frequency obtained by heterodyning the local oscillator signal and incoming r-f signal in a superheterodyne receiver.

LIMITER—An FM receiver stage which removes amplitude variations from the FM signal by cutting off all peaks exceeding a certain amplitude.

IMPORTANT DEFINITIONS (Continued)

MODULATED STAGE—The r-f amplifier stage of a transmitter in which the intelligence signal modulates the radio frequency carrier wave.

MODULATING SIGNAL—A signal which causes a variation of some characteristic of a carrier.

MODULATOR—The final audio amplifier of a transmitter, which supplies the necessary audio power for modulation.

MULTIPLEXING—The transmission of two or more signals using a common carrier wave or transmission line.

RADAR—A contraction of the term RAdio Detecting And Ranging. The use of radio to determine the direction and range or distance of an object.

RADIO SPECTRUM—A range of frequencies from 10 kilohertz to 30,000 megahertz, used for various types of radio transmissions.

SYNCHRONIZING PULSE—A pulse added to the video output signal of a television camera for the purpose of synchronizing television receivers with the transmitter.

TELEMETRY—A system of taking measurements at a remote location and reproducing the measurements at a more convenient location, to be displayed or recorded.

TRANSCEIVER—A two-way communication radio combining both a transmitter and receiver in a single housing.

VERTICALLY POLARIZED—Transmission of radio waves in such a way that the electric field of the wave is vertical or at right angles to the earth's surface.

VIDEO SIGNAL—That portion of a television signal which consists of the picture intelligence.

PRACTICE EXERCISE SOLUTIONS

1. A system which permits an exchange of information between two points.

2. The maximum distance between the person speaking and the person listening is relatively short.

3. wires

4. Speech, music and picture intelligence are three of the most common types of intelligence transmitted by radio waves. Morse code, control signals and signals related to measured data are other examples.

5. False—The audio signals are combined with a radio frequency carrier, and the combined signal is then radiated into space.

6. The FCC regulates all wire and radio communications in the United States, its possessions and territories. This does not include communications facilities operated by the federal government.

7. False—The standard broadcast band is from 535 to 1605 kHz which is in the Medium Frequency range.

8. (a) 10 kHz.

9. Amplitude modulation is a method of impressing low-frequency signals on a high-frequency carrier so that the amplitude of the carrier varies according to the changes in amplitude of the low-frequency signal.

10. vertically

11. The superheterodyne receiver.

12. You change the resonant frequency of those circuits. This, in turn, determines which carrier frequency is passed on to the rest of the receiver.

13. (b) i-f signal.

14. False—The demodulator changes the i-f signal to an audio frequency signal.

15. Noise interference can be greatly reduced with this system.

16. 88 MHz to 108 MHz.

17. ±75 kHz for a total swing of 150 kHz.

18. horizontally

PRACTICE EXERCISE SOLUTIONS (Continued)

19. (b) the physical construction of the transmitting antenna.

20. Most noise signals cause amplitude modulation of a transmitted wave, and thus are detected right along with the desired signals in an AM system. In FM, the intelligence is in the form of frequency variations, and any amplitude variations can be removed by a limiter to reduce interference.

21. False—The FCC allocates TV broadcast channels in both the VHF and UHF bands.

22. (b) 174 to 216 MHz.

23. 6 MHz.

24. (a) amplitude modulated.

25. (b) frequency modulated.

26. 4.5 MHz.

27. The sync and blanking pulses make it possible to lock the picture formed on the TV receiver screen in step with the picture produced in the camera tube.

28. True—The picture or video section compares to an AM broadcast station. The sound section compares to an FM broadcast station.

29. A system of making measurements from a distance.

30. True

31. 216 to 220 MHz, 1435 to 1535 MHz, and 2200 to 2300 MHz.

32. False—The maximum deviation is ±125 kHz for a total swing of 250 kHz.

33. The purpose of multiplexing is to transmit more than one type of information with one transmitter.

34. (a) frequency division multiplexing.

35. (b) time division multiplexing.

36. Marine, Aeronautical, Public Safety, Industrial, Land Transportation, Personal and Disaster communications.

37. True

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7450A
EXAMINATION CHECK SHEET

1. A - THE MOST COMMON INTERMEDIATE FREQUENCY USED IN AM BROADCAST SUPERHETERODYNE RECEIVERS IS -- 455 kHz.
The figure of 455 kHz is a compromise between having the intermediate frequency low enough to provide high gain and high enough to eliminate interference.

2. D - THE TYPE OF MODULATION IN TV SIGNALS IS -- AMPLITUDE MODULATION FOR VIDEO AND FREQUENCY MODULATION FOR SOUND.
The Federal Communications Commission requires that the forms of modulation be AM for the video and FM for the sound signals.

3. A - NOISE DUE TO ELECTRICAL INTERFERENCE IS GREATLY REDUCED IN AN FM RECEIVER BY -- A LIMITER.
Electrical interference is generally in the form of amplitude modulation and the limiter stage removes all amplitude variations from the signal.

4. B - TV CHANNEL 4 COVERS A RANGE OF -- 66-72 MHz.
Each TV channel is 6 MHz wide. Since Channel 2 starts at 54 MHz (54-60 MHz), Channel 3 covers a range of 60-66 MHz and Channel 4 covers a range of 66-72 MHz.

5. A - WHAT IS THE LOCAL OSCILLATOR FREQUENCY IN AN FM BROADCAST RECEIVER WHEN IT IS TUNED TO 103.5 MHz? (ASSUME THAT THE LOCAL OSCILLATOR IS OPERATING ABOVE THE DESIRED SIGNAL AND THE STANDARD FM INTERMEDIATE FREQUENCY IS EMPLOYED.) -- 114.2 MHz.
The local oscillator should operate 10.7 MHz above 103.5 MHz, or 114.2 MHz.

6. C - IN RADIO TELEMETRY, MORE THAN ONE CHANNEL OF INFORMATION CAN BE TRANSMITTED USING A COMMON CARRIER FREQUENCY BY USING A PROCESS CALLED -- MULTIPLEXING.
Either frequency division or time division multiplexing may be used.

7. B - TWO-WAY POLICE COMMUNICATIONS IS CLASSIFIED AS -- PUBLIC SAFETY SERVICE.
Police, fire department and like services fall under the classification of Public Safety service.

8. D - A TWO-WAY COMMUNICATIONS UNIT WHICH CONSISTS OF BOTH A RADIO TRANSMITTER AND RECEIVER IS CALLED A -- TRANSCEIVER.
Although a transceiver may consist of a separate transmitter and receiver, many transceivers share common circuits between the receiver and transmitter resistors.

9. A - THE LIGHT REFLECTED FROM THE REVOLVING DRUM OF A FACSIMILE TRANSMITTER IS PICKED UP BY A -- PHOTOELECTRIC CELL.
The photoelectric cell converts the light variations into an electric signal.

10. C - WHEN A RADAR TRANSMITTER IS SENDING OUT A PULSE OF R-F ENERGY, THE T-R SWITCH CONNECTS THE TRANSMITTER TO THE -- ANTENNA.
During the "listen" period, the T-R switch connects the receiver to the antenna.

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QUESTIONS

IMPORTANT—These instructions **MUST** be accurately followed to avoid loss, or errors in grading.

Indicate your answer on this sheet by filling in the box for the most correct answer to each question, as illustrated in the example below.

When all questions have been answered, place the answer card in the proper position to line up the boxes on the card with the boxes on the sheet.

Next, copy the complete lesson code into the space provided on the card, and fill in the answer boxes to correspond with those previously filled in on this sheet.

Before mailing, be certain your correct student number, name and address appear on the card.

LESSON CODE
7450A

Example: A foot is equal to
A ■ B ☐ C ☐ D ☐
(A) 12 inches. (B) 36 inches. (C) 6 inches. (D) 24 inches.

1. A ☒ B ☐ C ☐ D ☐
The most common intermediate frequency used in AM broadcast superheterodyne receivers is
(A) 455 kHz. (B) 535 kHz. (C) 10 kHz. (D) 1605 kHz.

2. A ☐ B ☐ C ☐ D ☒
The type of modulation in TV signals is
(A) amplitude modulation for both video and sound. (B) amplitude modulation for sound and frequency modulation for video. (C) frequency modulation for video and sound. (D) amplitude modulation for video and frequency modulation for sound.

3. A ☒ B ☐ C ☐ D ☐
Noise due to electrical interference is greatly reduced in an FM receiver by
(A) a limiter. (B) a discriminator. (C) an audio amplifier. (D) an r-f amplifier.

4. A ☐ B ☒ C ☐ D ☐
TV channel 4 covers a range of
(A) 54-60 MHz. (B) 66-72 MHz. (C) 60-66 MHz. (D) 72-78 MHz.

5. A ☒ B ☐ C ☐ D ☐
What is the local oscillator frequency in an FM broadcast receiver when it is tuned to 103.5 MHz? (Assume that the local oscillator is operating above the desired signal and the standard FM intermediate frequency is employed.)
(A) 114.2 MHz. (B) 103.955 MHz. (C) 92.8 MHz. (D) 103.045 MHz.

6. A ☐ B ☐ C ☒ D ☐
In radio telemetry, more than one channel of information can be transmitted using a common carrier frequency by using a process called
(A) modulation. (B) heterodyning. (C) multiplexing. (D) beating.

7. A ☐ B ☒ C ☐ D ☐
Two-way police communications is classified as
(A) Aeronautical service. (B) Public Safety service. (C) Industrial Radio service. (D) Land Transportation service.

8. A ☐ B ☐ C ☐ D ☒
A two-way communications unit which consists of both a radio transmitter and receiver is called a
(A) modulator. (B) television receiver. (C) local oscillator. (D) transceiver.

9. A ☒ B ☐ C ☐ D ☐
The light reflected from the revolving drum of a facsimile transmitter is picked up by a
(A) photoelectric cell. (B) preamplifier. (C) transmitter. (D) cathode ray tube.

10. A ☐ B ☐ C ☒ D ☐
When a radar transmitter is sending out a pulse of r-f energy, the T-R switch connects the transmitter to the
(A) receiver. (B) cathode ray tube. (C) antenna. (D) pulse timer.

PRACTICE EXERCISE SOLUTIONS (Continued)

38. (a) 6 to 50 kHz.

39. (b) frequency modulation.

40. To make the signal audible.—CW is an unmodulated carrier, and thus produces no sound from the speaker or headphones. A BFO produces a signal that beats with the i-f signal to produce an audible signal.

41. (b) an automatic noise limiter.

42. True

43. A facsimile system can be used to send printed copy, pictures, maps or any other printed information.

44. False—The image is formed on a light-sensitive paper by the variations of light from a recording lamp.

45. True

46. Approximately 1000 to 30,000 megahertz.

47. False—The distance is determined from the interval between the time the pulse is transmitted and the time the echo returns.

QUESTIONS

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UNIT EXAMINATION FOR
COURSE 74

This examination contains a number of different type questions: multiple choice, true or false, fill in the blank and direct question. To assist us in grading, please print your answers clearly on the answer sheet. **COMPLETE THE PORTION STATING YOUR NAME, ADDRESS AND STUDENT NUMBER ON THE ANSWER SHEET AND SEND ONLY THE ANSWER SHEET FOR GRADING.** Retain the examination questions for your records.

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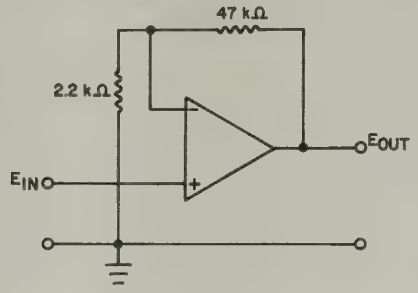
1. What is the voltage gain of the operational amplifier shown below? The open-loop gain is sufficiently high.

$A_V =$ 22.4



$\frac{47k + 2.2k}{2.2\,K}$ $\frac{49.2K}{2.2k}$

22 | 492 = 22.36
44
52
44
80
66
140
132

2. The differential amplifier has an output voltage when (A) the same positive voltages are applied to both inputs. [✓ (B)] a differential voltage signal is applied between the inputs. (C) the same negative voltages are applied to both inputs.

3. Compared with equivalent discrete circuits, the number of transistors used in integrated circuits is usually [✓ (A)] more. (B) the same number. (C) less.

4. A transistorized or IC cascode amplifier consists of a common-emitter stage followed by a common-base stage.

5. Integrated circuits have the advantage over discrete circuits in having more closely matched components and thermal characteristics. [✓ True] or False?

6. Perfect power supply regulation is (A) 100%. (B) 50%. [✓ (C)] 0%.

7. Load regulation permits the output voltage to change in accordance with input voltage variations. True or [✓ False]?

8. The two major factors most commonly considered in regulated power supplies are [✓ (A)] output voltage and current. (B) input voltage and current. (C) input and output impedance.

9. What are the two main classes of voltage regulators? series shunt

10. Integrated circuits have many limitations and therefore may be used only for very restricted applications in regulated power supplies. True or [✓ False]?

11. What is the unit of measure of the intensity of a light source? candlepower

12. A significant feature of the photodiode, which enables its wide usage in many applications, is fast response time. [✓ True] or False?

13. Why is the output current of a photo Darlington amplifier so much higher than the output current of a single phototransistor? ________
two transistor connected so that current gain is product

14. What is the name applied to a combination of two photoelectric devices, one of which is a light source and the other a device that responds to the source? optical coupler

15. Is forward or reverse bias required to enable the LED to operate?
____

16. When an electric meter is connected in parallel with a component in a circuit, a new circuit is formed that consists of the electric meter's power supply resistance and the component's resistance. True or [✓ False]?

17. The differential amplifier used in the DeVry TRVM protects the meter movement from being damaged by excessive current. [✓ True] or False?

18. When the FUNCTION switch on the DeVry TRVM is placed in the AC position, an associated calibration control is placed in [✓ (A)] parallel with the meter movement. (B) series with the meter movement.

19. The most common TRVM accessories are cable assemblies, probes and shunts. [✓ True] or False?

20. A special type of electronic meter is the (A) galvanometer. (B) volt-ohm multimeter. [✓ (C)] digital multimeter.

21. For greatest trace accuracy, the voltage between the vertical deflection plates should have a no-signal potential of (A) the deflection output stage supply voltage. [✓ (B)] zero volts. (C) 100 volts dc.

22. For greatest trace accuracy, the vertical amplifier input impedance should be (A) very low. [✓ (B)] very high. (C) medium.

23. The horizontal sweep synchronization is always controlled by the output of the vertical amplifier. True or [✓ False]?

24. The aquadag crt coating in an oscilloscope is maintained at a very high positive potential with respect to ground. [✓ True] or False?

25. Deflection factor is given in (A) scale divisions per volt. (B) vertical volts per horizontal drive volts. [✓ (C)] volts per scale division.

26. Rear projection displays use what type of light source? ________
incandescent

27. Gas discharge displays use what type of light source? ionization

28. The color of fluorescent segment displays is basically orange. True or [✓ False]?

29. Gallium phosphide LED's are available in three colors. Name them. green, yellow, red

30. What display device is utilized for displaying large amounts of digital information? CRT

31. A worn commutator and an incorrect brush spring tension are two main causes of brush ripple. [✓ True] or False?

32. Torque is measured in foot-pounds. True or [✓ False]?

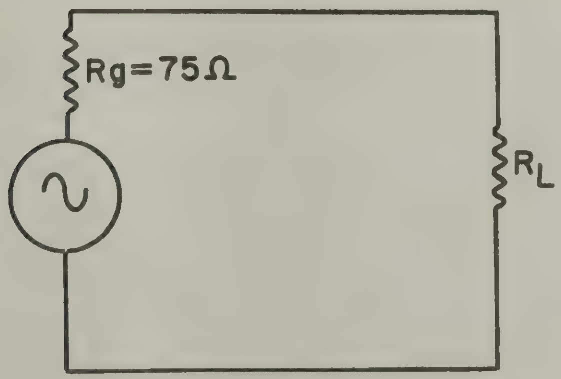
33. The field and armature cores are constructed of a stack of thin pieces of sheet iron coated with insulating varnish to reduce eddy currents. [✓ True] or False?

34. The power factor of an alternating current circuit may have any value between 0 and 1. [✓ True] or False?

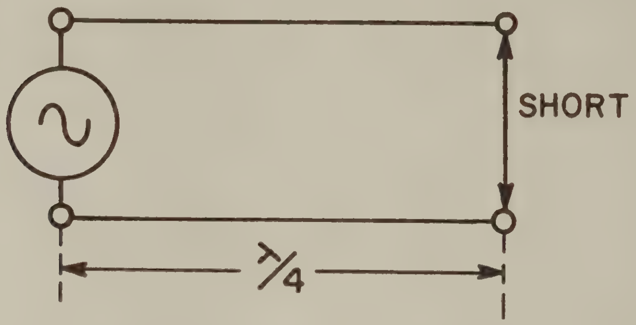
35. AC motors and generators usually operate with a power factor of less than one. [✓ True] or False?

36. If a transformer has an impedance ratio of $^1/_{25}$, the turns ratio is then (A) $^1/_{25}$. (B) $^1/_{625}$. [✓ (C)] $^1/_5$. (D) $^1/_{50}$.

37. In the circuit shown below, what value of load impedance, R_L, will result in maximum power transfer to the load? 75Ω



38. Referring to the shorted quarter wavelength transmission line shown below, as far as the source is concerned the transmission line appears as a (A) very low impedance. (B) series resonant circuit. [✓ (C)] parallel resonant circuit. (D) reactive load.



39. What is the standing wave ratio if a transmission line with a characteristic impedance of 75Ω is connected to a load impedance of 300Ω? 4:1

40. To find the percent of modulation, the modulation envelope patterns displayed on an oscilloscope must always be measured in centimeters. True or False?

41. In high-level modulation, the r-f stages preceding the modulated stage are not necessarily operated as linear amplifiers. [✓ True] or False?

42. In an FM system, the total radiated power varies with the percent of modulation. True or [✓ False?]

43. In a superheterodyne receiver the (A) radio frequency is always the same. [✓ (B)] intermediate frequency is always the same.

44. In single sideband reception, the carrier signal is inserted into the receiver by the beat frequency oscillator.

45. The federal agency which regulates radio communications in the United States is called the FCC.

46. Two standard broadcast stations are never assigned the same frequency. True or [✓ False]?

47. In television broadcasting, the sound signal is (A) amplitude modulated. [✓ (B)] frequency modulated.

48. The two general methods of multiplexing are FREQUENCY DIVISION and time division.

49. Marine or Maritime radio communication services of U.S. registry between ship to ship do not need FCC licensing of their stations. True or [✓ False]?

50. Television broadcasting is an example of two-way radio communications. True or [✓ False]?

APR 26 76

APR 14 1976
DeVRY INSTITUTE OF TECHNOLOGY

UNIT EXAMINATION 74
ANSWER SHEET

GRADE 96

INSTRUCTOR W. ROZKO

Name Kent M. Bestwick

Address P.O. BOX 329

City FT. HUACHUCA

State/Province ARIZONA Zip Code 85613

Student No. K36 739 1GW

UE74B APR 14 1976

Write your answers in the space provided. Be sure to include units, such as volts, μF, etc. where necessary. **RETURN ONLY THE ANSWER SHEET FOR GRADING.** Keep the exam for your records.

1. 22.4
2. B
3. A
4. Emitter, Base
5. True
6. C
7. False
8. A
9. Series & Shunt
10. False
11. Candlepower
12. True
13. Two transistors connected so that current gain is product of each current gain
14. Optical coupler
15. Forward
16. False
17. True
18. ✗ A
19. True
20. C

(Continued on reverse side)

21. B

22. B

23. False

24. True

25. C

26. Incandescent

27. Ionization

28. False

29. Green, yellow, Red

30. Cathode Ray Tube

31. True

32. False

33. True

34. True

35. True

36. C

37. 75Ω

38. C

39. 4:1

40. False

41. True

42. False

43. B

44. Beat Frequency Oscillator

45. Federal Communications Commission

46. False

47. B

48. Time Division

49. False

50. False

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